# Model-Based Analysis of Role-Based Access Control

## Thesis

# Model-Based Analysis of Role-Based Access Control

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# Abstract

Model-Driven Engineering (MDE) has been extensively studied. Many directions have been explored, sometimes with the dream of providing a fully integrated approach for designers, developers and other stakeholders to create, reason about and modify models representing software systems.

Most, but not all, of the research in MDE has focused on general-purpose languages and models, such as Java and UML. Domain-specific and cross-cutting concerns, such as security, are increasingly essential parts of a software system, but are only treated as second-class citizens in the most popular modelling languages. Efforts have been made to give security, and in particular access control, a more prominent place in MDE, but most of these approaches require advanced knowledge in security, programming (often declarative), or both, making them difficult to use by less technically trained stakeholders.

In this thesis, we propose an approach to modelling, analysing and automatically fixing role-based access control (RBAC) that does not require users to write code or queries themselves. To this end, we use two UML profiles and associated OCL constraints that profide the modelling and analysis features. We propose a taxonomy of OCL constraints and use it to define a partial order between categories of constraints, that we use to propose strategies to speed up the models' evaluation time. Finally, by representing OCL constraints as constraints on a graph, we propose an automated approach for generating lists of model changes that can be applied to an incorrect model in order to fix it. All these features have been fully integrated into a UML modelling IDE, IBM Rational Software Architect.

# Declaration

All the work in this dissertation describes original contributions of the author.

- Montrieux, Lionel; Wermelinger, Michel and Yu, Yijun (2011). Tool support for UML-based specification and verification of role-based access control properties. In: *8th European Software Engineering Conference and the ACM SIGSOFT Symposium on the Foundations of Software Engineering, pp. 456-459*, 4-9 Sep 2011, Szeged, Hungary (tool demo).

- Montrieux, Lionel; Wermelinger, Michel and Yu, Yijun (2011). Challenges in Model-Based Evolution and Merging of Access Control Policies. In: *12th International Workshop on Principles on Software Evolution @ ESEC/FSE 2011, pp. 116-120*, 5-6 Sep 2011, Szeged, Hungary.

- Montrieux, Lionel; Yu, Yijun; Wermelinger, Michel and Hu, Zhenjiang (2013). Issues in representing domain-specific concerns in model-driven engineering. In: *5th Workshop on Modeling in Software Engineering @ ICSE 2013*, 18-19 May 2013, San Francisco.

- Montrieux, Lionel; Yu, Yijun and Wermelinger, Michel (2013). Developing a domain-specific plug-in for a modelling platform: the good, the bad, the ugly. In: *3rd Workshop on Developing Tools as Plug-ins @ ICSE 2013*, 21 May 2013, San Francisco.

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*"Being abstract is something profoundly different from being vague ... The purpose of abstraction is not to be vague, but to create a new semantic level in which one can be absolutely precise."*

— Edsger W. Dijkstra

# Chapter 1.

# Introduction

## 1.1. Motivation

Model-Driven Engineering (MDE) is a software engineering paradigm whose basic assumption is *"the consideration of models as first class entities. A model is an artifact that conforms to a metamodel and that represents a given aspect of a system"* [18]. The Object Management Group (OMG) is an organisation that proposes a set of standards to implement MDE, such as the Unified Modeling Language (UML) [76], the Meta-Object Facility (MOF) [73], and the Object Constraint Language (OCL) [75]. The OMG uses these standards to propose its Model-Driven Architecture (MDA), an approach for "specifying a system independently of the platform that supports it", "specifying platforms", "choosing a particular platform for the system", and "transforming the system specification into one for a particular platform" [67]. Specifications that are independent of the platform are called *Platform-Independent Models (PIM)*, while specifications for a particular platform are called *Platform-Specific Models (PSM)*.

In their empirical assessment of MDE in industry, Hutchinson et al. [46] have surveyed experienced modellers in companies that "*have been using models as a primary development artefact*" [46, p. 471]. They found that "*MDE users employ multiple modeling languages. Almost 85% of respondents make use of UML and almost 40% use a DSL* [Domain-Specific Language] *of their own design.* [...] *A quarter of respondents* [...] *use a DSL provided by a tool vendor*" [46, p.474]. This shows that UML is widely adopted amongst MDE practitioners, and that domain-specific languages (DSL) are also used by a significant proportion. By far the most used type of diagrams are class diagrams (almost 90% of respondents), followed by activity diagrams (around 55%) and use case diagrams (almost 40%). DSL diagrams come in sixth position with less than 10%, after sequence diagrams and state machine diagrams [46, p.474].

In her study of UML in practice, Petre [83] interviewed 50 software engineers from "*a wide range of industrial settings*" [83, p. 3]. It emerged from the interviews that the

majority of them do *not* use UML at all (70%), 22% of them use it selectively, and 6% use it for code generation [83, p. 3]. Class, sequence and activity diagrams were found to be the most widely used, which confirms Hutchinson et al.'s findings. Two of the criticisms against UML identified by Petre are particularly important for this work: the first one is that some practitioners note that "*the complexities of the notation limited its utility - or demanded targeted use - in discussions with stakeholders* [...] *The best reason not to use UML is that it is not 'readable' for all stakeholders*" [83, p. 4], and the second one is that "*there is no check on consistency, redundancy, completeness or quality of the model what so ever*" [83, p. 5].

Selic gives directions on what is required to increase industry adoption of MDE [96]. He discusses cultural and social factors, economic factors, and technical factors. In this dissertation, we focus on the technical factors. Amongst the challenges in this category, he identifies scalability, usability, model validation and synchronisation, modelling language design and specification, and model transformations.

Most of the research conducted in MDE has focused on general-purpose models, and ways of transforming them, evolving them, analysing them, or turning them into code. General-purpose models, just like their general-purpose language counterparts, do not always make it very easy to represent domain-specific concepts. Addressing this problem in the context of MDE can be done in two different ways. The first one uses domain-specific annotations on general-purpose models. Here languages used for these annotations are called *domain-specific modelling annotations languages (DSMAL)*. The other school of thought ignores the general-purpose models, and favours models that *exclusively* represent the domain-specific concepts, much like domain-specific programming languages. These are called *domain-specific modelling languages (DSML)*.

In this dissertation, we argue that both approaches can complement each other, and apply them to represent a very important concern in software development: security, and in particular access control.

Security is a growing concern in the software engineering community [68]. With software systems being increasingly connected and handling large amounts of data, both the attack surface of software systems and the potential value of the data they contain to prying eyes have gone up dramatically. Now more than ever, it is essential to protect access to data in order to prevent it from being leaked to unauthorised third parties. Access control is the part of computer security that deals with this issue of deciding who gets access to what data and operations, and under which circumstances. Getting access control policies exactly right is *hard*, if not impossible [94]. Giving users too much access to data or processes increases the risk of leaks and misuse of information, whilst not giving them enough permissions will prevent them from using the system as they should be able to.

Leaving security concerns to the end of the development cycle often leads to poorly protected systems. Hence, Fernandez-Medina et al. [30] argue that security would benefit from being taken into account from the first stages of the development process, e.g. as part of an MDE process. This would make it easier to keep track of security requirements and make sure that the security measures actually enforce those requirements, to handle change and its impact on security, and to communicate the security measures to the stakeholders.

Beyond the "simple" definitions of DSMLs or DSMALs, there exist many approaches that attempt to make domain-specific concepts first class citizens in MDE. This is certainly true of security, and access control in particular, where approaches such as SecureUML [8], UMLsec [48] and others allow for the modelling of access control properties, and sometimes their analysis with regard to security requirements. Most of these approaches use the

role-based access control (RBAC) model, in which users are not directly given permissions. Instead, they are assigned roles, and roles are assigned permissions.

While these approaches do allow one to take RBAC concerns into account early in the development cycle, they still suffer some limitations. Some of them do not support the entire RBAC standard, although others may support it entirely, and even support further constructs that are not available in the standard. These approaches also often require users to write queries themselves, or to interpret complex outputs, which could make adoption by users with little technical background more difficult. Finally, while these approaches are good at identifying errors in RBAC models, they do not help users in fixing those errors, which can be a difficult and time-consuming process if done manually.

## 1.2. Research Objectives

The purpose of this dissertation is to explore and propose an approach for the modelling, evaluation, analysis and fixing of domain-specific models, using both a DSML and a DSMAL. The focus will be on the design compliance to RBAC, a widely-used and standardised access control model. We will be looking at the following research question: *How can we design, analyse and fix RBAC concepts as part of an MDE process, in a way that does not require users to write complex queries or code themselves, and using (almost) exclusively OMG standards?*

In particular, we will explore three MDE-related activities:

**Modelling** Perhaps the most important activity is the ability to model RBAC-specific concerns;

**Model analysis** The ability to analyse the models against user-defined requirements expressed as a form of tests that we call *scenarios*, and to perform further analysis

on the model for well-formedness, scenario coverage, model completeness, scenario satisfiability, and the identification of redundancies;

**Fixing incorrect models** When the evaluation of the models exposes errors, correcting them can be very difficult to do manually: fixing an error in one place may raise new errors, creating a long and error-prone cycle of error fixing. Therefore, an automated discovery of possible solutions to an erroneous model may be of great help to the stakeholders.

Because it is arguably the most widely known modelling language, and because of its extension mechanism called profiles and the availability of UML modelling tools and platforms, we selected UML to develop our approach. Bran Selic's methodology for DSML development [95] can be used not only to develop DSMLs, but also DSMALs, which is why it has been selected for the development of both languages. Selic's methodology proposes a systematic way of developing a UML profile to implement a DSML, from a model of the domain-specific concepts to be represented. The choice to develop both a DSML and a DSMAL was made because each of them is better suited for some activities.

Many stakeholders are likely to use models produced as part of an MDE approach: developers of course, as well as model designers, but also customers and other stakeholders, who may not all have experience and knowledge in software engineering. Similarly, in the case of domain-specific models, not all the stakeholders are necessarily *au fait* with the specifics of the particular domain being studied. This is especially true of security, which is a notoriously hard domain. It is therefore crucial for the proposed approach to be accessible to non-experts. In particular, users should not be required to write any code or queries themselves. Instead, the analysis of models should be automated, and the queries and code should be hidden from the users.

This dissertation proposes four contributions:

**Modelling and analysing RBAC concerns** using two UML profiles;

**A classification of OCL constraints** and the use of said classification to define a partial order between the categories, to improve the evaluation speed and the user feedback by only evaluating constraints if preconditions are satisfied;

**The automated generation of fixes** that can lead an incorrect model into a correct state;

**Two performance evaluations,** one of the efficiency of the evaluation strategies proposed, and one of the automated generation of model fixes.

We present `rbacUML`, an approach for modelling and analysing RBAC properties and requirements on UML models. At the core of `rbacUML` are two UML profiles (`rbacUML` and `rbacDSML`) that extend the UML meta-model. The focus is on using standard UML technologies that designers may already know, in order to make the `rbacUML` approach as easy to use as possible. Whilst the `rbacUML` profile defines a DSMAL, the `rbacDSML` profile defines a DSML, both to express the access control properties and requirements. Requirements can be expressed in the following forms:

**scenarios** specific actions that a particular user, given a set of active roles, *must* be able to perform;

**anti-scenarios** specific actions that a particular user, given a set of active roles, *cannot* perform.

Both profiles are made of three parts:

**The configuration** defines domain concepts (users, role hierarchies, etc.);

**The policy** identifies protected resources and defines their access requirements;

**The scenarios and anti-scenarios** ensure that the model enforces the expected access control requirements.

The first two follow traditional access control specifications, while the last one is required solely for testing and verification purposes.

To address the "breadth of evaluation" issue, `rbacUML` provides the following evaluation capabilities:

**well-formedness** Are there any syntactic or type errors in the model?

**verification** Are the scenarios and anti-scenarios enforced by the model?

**completeness** Is there anything missing in the model, e.g. are there users that have been assigned no roles, or permissions that are not associated with any role?

**coverage** Which parts of the model are covered by access control (anti-) scenarios?

**satisfiability** Are some resources impossible to access, or some scenarios impossible to complete, no matter which user carries them out?

**redundancy** Are there access control elements that are redundant, and could safely be merged?

All the above analyses are implemented using OCL queries, the OMG's standard language for model queries. The last four allow users to identify "model smells", areas where the model may require some attention, but that are not necessarily errors.

As models grow, so does the number of OCL queries to evaluate, therefore increasing the evaluation time. Moreover, the result of the evaluation of some constraints may not always be useful to the designers. Moreover, lots of feedback can be given to the designers, which may be confusing. By introducing a categorisation of OCL queries, and by providing a partial order between the different categories, the proposed strategies will

not only increase the verification speed by only evaluating the constraints required, but also reduce the amount of unwanted feedback given to the designers.

In order to fix erroneous models in a way that is useful to stakeholders, two properties need to be guaranteed:

**Correctness** Any solution generated must produce a correct model;

**Completeness** All possible solutions must be proposed, for the stakeholders to be able to choose the most appropriate solution.

The performance of the `rbacUML` models analysis is evaluated, as well as the performance of the time reduction strategies proposed. The different fixing strategies proposed are also evaluated and compared.

## 1.3. Organisation of this Dissertation

This dissertation comprises 6 chapters. The first one is this introduction. Chapter 2 provides background and a review of the existing literature appropriate for this work. Chapter 3 presents, discusses and compares the `rbacUML` DSMAL and the `rbacDSML` DSML. `rbacDSML` is used in Chapter 4 to propose a solution to fix incorrect models. Chapter 5 then presents the implementation of `rbacUML` and `rbacDSML`, and evaluates the performance of the proposed model analysis and fixing approach. Chapter 6 suggests future work and ends with concluding remarks.

As stated earlier in the declaration, some of the material in this dissertation has been published in peer-reviewed venues. Material from our tool paper [64] can be found in Chapter 5; material from our paper on challenges in model-based evolution and merging of access control policies [63] is available in Chapters 2 and 6; material from our paper on the representation of domain-specific concerns in MDE [66] is in Chapters 3 and 6;

material from our paper on plug-in development on modelling platforms [65] is found in Chapter 5.

# Chapter 2.

# Literature Review

This chapter reviews the literature relevant to this dissertation in three sections. The first section introduces the concepts of model-driven engineering (MDE). The second section is focused on access control, and how access control models evolved over time. It also discusses the latest advances in the evaluation of access control policies. Finally, the third section unites both areas by discussing existing approaches that attempt to integrate access control concerns into MDE approaches. The strengths and weaknesses of these approaches are discussed, highlighting the gap that this dissertation attempts to fill.

## 2.1. Model-Driven Engineering

The use of models to reduce software complexity has been advocated for decades in the software engineering community [93]. The OMG, for example, proposes a four-layer architecture [13], summarised in Table 2.1. The lowest level (M0), at the bottom of the table, is an instance of a model, i.e. the real system. The next level (M1) is the model level, which conforms to a meta-model on level M2, itself conforming to the meta-meta-model on the highest level (M3) [13]. According to Bézivin, a model conforms to a meta-model *"if and only if each model element has its metaelement defined in the metamodel"* [14]. In the same manner, a meta-model conforms to a meta-meta-model if and only if each meta-model element has its meta-element defined in the meta-meta-model.

**Table 2.1.:** Table of the OMG organisation in a four-level architecture

| Level | Name | Description |
|---|---|---|
| M3 | Meta-meta-model | describes meta-models |
| M2 | Meta-model | describes the elements of a model, conforms to M3 |
| M1 | Model | describes a system, conforms to M2 |
| M0 | Instance | describes an instance of the model, conforms to M1 |

Several organisations and companies have proposed platforms to support MDE, such as Microsoft's Software Factories [37] or OMG's MDA [102]. The focus of this dissertation will be on OMG's set of standards, which includes the widely known Unified Modelling Language (UML).

In this dissertation, we focus on the design level. The argument made by Ferandez-Medina et al. [30] is that, since design often comes before implementation, at least in traditional development models such as the waterfall or the V model, a way of taking security into account early in the software development cycle is to express it at the design level. Furthermore, the design level already provides sufficient detail (e.g. the resources that need to be protected) to reason about access control, making it a sensible choice for early analysis. In some software engineering practices, the design level comes after the elicitation of requirements. Therefore, we assume that the specific access control requirements to be enforced have already been defined. While expressing and verifying access control requirements could perhaps already be done at that level, it is out of the scope of our approach. Such a solution would not replace our approach, but complement it. First, because the design level contains more details than the requirements level. Second, because while security should be taken into account as early as possible [30], traceability of security concerns throughout all the phases of the software development process is also essential.

The proposed approach is clearly solution-oriented, and assumes that the solution to a real world problem has been defined. The focus is on how to gain confidence in the fact that the software actually enforces that solution, i.e. conforms to the access control requirements, not how the solution has been found or whether or not it actually solves the real world problem.

### 2.1.1. MDE using OMG Standards

The Object Management Group (OMG) [74] is a not-for-profit consortium that *"develops enterprise integration standards for a wide range of technologies"*. In 2001, the OMG launched its own initiative to support model-driven engineering: Model-Driven Architecture (MDA) [102]. MDA is *"the realisation of model engineering principles around a set of OMG standards"* [13]. Such standards include the Unified Modeling Language (UML), the Object Constraint Language (OCL), and the Meta-Object Framework (MOF).

MDA introduces a key distinction between platform-independent models (PIM) and platform-specific models (PSM). The former are the higher-level representations of a software system, which are meant to be later specialised into PSMs as the choice of platform is made. The OMG defines PIM as *"a formal specification of the structure and function of a system that abstracts away technical detail"*, while PSM is defined as *"a specification model of the target platform"*. It is an intermediate step between the PIM and the implementation. This distinction has been introduced as the OMG was facing a rise in the number of frameworks and middlewares that their members were using. By specifying PIM models, one could describe a system without taking its implementation into account, leaving the PSM details for when the target platform was chosen. This allows one to easily change the platform as well, without affecting the PIM at all.

Steve Cook retraces the history of UML and states that it finds its roots in the development of object-oriented languages, as well as the graphical design languages of the early 1990s [22]. In 1994, a study commissioned by the OMG concluded that standardisation of these languages was required. A consultation process was then engaged, that led to a submission by Rational Software Corporation of the Unified Modeling Language 1.0. The first specification published by OMG was UML 1.1 [77], the result of a compromise over the several submissions to the consultation. In particular, OCL was integrated into the publication, but actually came from IBM/ObjectTime's

**Table 2.2.:** The 4-layer structure of the UML architecture [55]

| Level | Name | Content |
|---|---|---|
| M3 | meta-meta-model | MOF meta-meta-model |
| M2 | meta-model | UML meta-model |
| M1 | model | UML analysis model (e.g. class diagrams) |
| M0 | instance | UML instance model (e.g. object diagrams) |

submission [112]. At the time, UML 1.1 supported 8 types of diagrams. Several refinements of UML were later published, until UML 1.4 in 2001 [78]. UML quickly became the most prominent modelling language in industry and academia [22]. A bigger overhaul of the UML standard was published in 2005, called UML 2.0 [79]. UML 2 was meant to address the issues of UML 1.x that had been raised by practitioners and academics. In particular, MOF [73] was introduced as "*a modelling language for specifying meta-models*", and used to formally define UML 2. UML loosely followed the 4-layers architecture from Table 2.1, as pointed out by Kobryn [55] and summarised in Table 2.2. The UML 2.x revision process continues to this day.

One important feature of UML is profiles [21]. Whilst UML is a general-purpose language, it can be extended with new constructs using the profile mechanism, which is essentially an extension of the UML meta-model using stereotypes and stereotype attributes, also called tagged values. UML profiles allow one to define domain-specific constructs to use with UML models. The OMG has released a few standardised UML profiles, such as the System Modeling Language (SysML) [80], or the profile for Modeling and Analysis of Real-time Embedded Systems (MARTE) [81].

UML 2.3 [76], the latest release, has 14 types of diagrams, divided largely into two categories: structural diagrams and behavioural diagrams. There is also a sub-category of behavioural diagrams called interaction diagrams:

- Structural diagrams

  - Profile diagrams
  - Class diagrams
  - Composite structure diagrams
  - Component diagrams
  - Deployment diagrams
  - Object diagrams
  - Package diagrams
- Behavioural diagrams
  - Activity diagrams
  - Use case diagrams
  - State machine diagrams
  - Interaction diagrams:
    * Sequence diagrams
    * Communication diagrams
    * Interaction Overview diagrams
    * Timing diagram

### 2.1.2. Model Transformations as Graph Transformations

Mens et al. have proposed a taxonomy of model transformations [60], and applied it to graph transformation tools [61]. This makes a lot of sense, since models are typically very much graph-like: in UML, for example, model elements are nodes, and

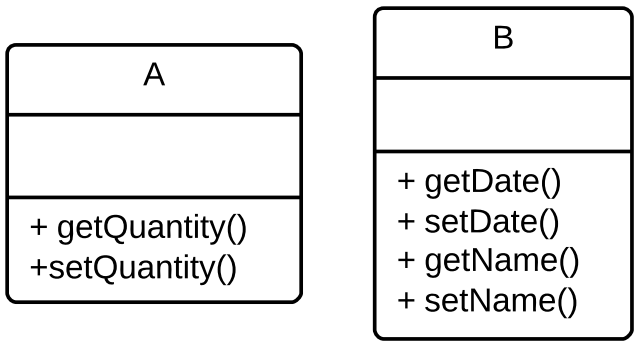
associations between elements are edges between nodes. It therefore makes sense to treat models as graphs, which allows one to apply graph theory principles and techniques to analyse and transform models. The graph-based model transformation tools they analysed are VIATRA [23], a model checking and verification tool; GReAT [104], a model transformation tool; Fujaba [17], a re-engineering tool; and AGG [1], a general-purpose graph transformation tool. The authors claim that their taxonomy is general enough to apply to other graph transformation tools as well.

Bergmann et al. [12] have successfully used graph transformations for several purposes, including live incremental transformations and model transformations by example. The former is really useful in a situation where several models need to be kept in sync. Instead of doing batch transformations to reflect changes from the source model to the target models, live incremental transformations provide an efficient way of performing the transformations continuously, by analysing the impact of each change to the model elements, and identifying which target elements may potentially be affected by each change. The latter allows one to semi-automatically define model transformations. The analysis of a few example transformations provided by the user allow the engine to derive possible transformation rules, that can then be applied to entire graphs.

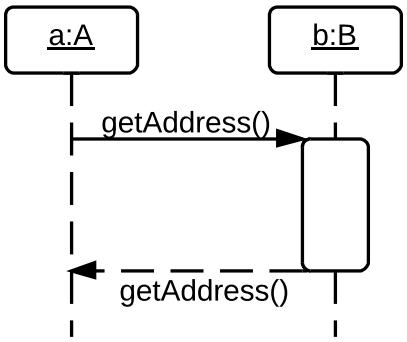
### 2.1.3. Inconsistency Detection and Resolution

During the MDE development cycle, it is likely that inconsistencies between parts of the models will occur. It is important to be able to detect those inconsistencies and resolve them. One should note that the process of inconsistency handling is very similar to the process of software merging, and therefore, some techniques developed for the former have been used in the latter, and vice-versa. By inconsistencies, we specifically mean contradictions, often between two different diagrams, in the same model. For example, Figure 2.1 shows a class diagram as well as a sequence diagram. The sequence diagram

represents a call from an object of type `A` to an object of type `B`, using its operation `getAddress()` that is not listed in the class diagram.




**(a)** Class diagram




**(b)** Sequence diagram

**Figure 2.1.:** A sample inconsistency between a sequence diagram and a class diagram

The first attempt at inconsistencies detection has been suggested by Finkelstein et al. [33] with their ViewPoints framework that allows each actor to have its own view of the system, consisting of only the diagrams that make sense to him/her.

Van Der Straeten et al. propose a two dimensional classification of inconsistencies [110] between class, sequence and state diagrams. The first dimension describes the type of affected model, according to MDA as described in section 2.1.1. Conflicts can arise between a model and a model, between a model and an instance, or between an instance and an instance. The second dimension describes which aspects of the model

are affected: behavioural or structural. Figure 2.3 presents the classification of the types of inconsistency conflicts Van Der Straten et al. detected.

**Table 2.3.:** Classification of inconsistency conflicts [110]

| | Behavioural | Structural |
|---|---|---|
| Model-Model | | dangling (type) reference, inherited association conflict |
| Model-Instance | incompatible definition | instance definition missing |
| Instance-Instance | invocable behaviour conflict, observable behaviour conflict, incompatible behaviour conflict | disconnected model |

Van Der Straeten et al. only describe two types of conflicts: instance definition missing, that *"occurs when an element definition does not exist in the corresponding class diagram"*, and incompatible behaviour, that *"indicate conflicting behaviour definitions between state diagram(s) and sequence diagram(s)"* [110].

Their proposal is not limited to a classification of inconsistencies, as they also propose to use description logic to maintain consistency between those diagrams (class, sequence and state) during software evolution [110]. They first define a UML profile to support consistency, and then translate it into description logic, which is a decidable subset of first order predicate logic. Their approach is limited as it only works on three types of UML diagrams.

Mens and Van Der Straeten later propose another approach, based on graph transformations and critical pair analysis [59]. Their proposal is an iterative process to detect and resolve inconsistencies by representing them as graph transformation rules. To detect inconsistencies, they define possible inconsistencies using graph transformation rules, and search the model for occurrences of structures, or the absence of some others. To resolve those inconsistencies, they specify several possible resolution rules. They use an extension of the AGG tool [1] to implement those graph transformations. The process

is incremental because resolving one inconsistency might lead to other inconsistencies (induced inconsistencies), or because several resolution rules might interfere with each other (conflicting resolutions). To avoid infinite iterations, they use critical pair analysis to avoid cycles in the resolution process.

Yet another approach to detecting inconsistencies is proposed by Blanc et al., and uses operation-based model construction [16], which *"represents models by sequences of elementary construction operations, rather than by the set of model elements they contain"* [16]. This approach has the advantage of being independent of any metamodel. It is, therefore, not limited to some types of UML diagrams like the solutions discussed earlier. It is inspired by the work of Lippe and Van Oosterom [57] in software merging that proposed an operation-based approach to software merging. By defining only four operations (`create`, `delete`, `setProperty` and `setReference`), one can build any model conforming to any metamodel using a sequence of atomic operations. Blanc et al. consider two kinds of consistency rules ([16]):

**structural consistency rules** define relationships that should hold between model elements regardless of how they have been constructed;

**methodological consistency rules** are constraints over the construction process itself.

Rules of both types are defined using predicate logic, and then checked using a Prolog engine. While this is a sound and well understood solution, it has the drawback of potentially leading to infinite loops. As opposed to Van Der Straeten et al. [110] who chose to use a subset of first order logic to avoid infinite loops, Blanc et al. decided to transfer the responsibility of ensuring that infinite loops will not happen to the transformation rule developers.

Another drawback of Blanc's approach is that the inconsistency checking process has to be run as a batch job, while it would be desirable for the application developer

to get instant feedback while the model is built. They addressed this problem later by providing an incremental detection approach that still uses operation-based model construction [15]. By using an incremental checking strategy instead of checking the whole model as a batch, the number of consistency rules to check is drastically reduced. To do so, they use equivalence class partitioning to classify the rules, and select those which are actually impacted by the changes that have been made. An impact matrix is then constructed to point out which operations might impact inconsistency rules. Since the inconsistency checking process is now much faster, it has been integrated into the Eclipse GMF modelling environment, as well as Rational Software Architect.

Realising that, even though progress had been made in inconsistency detection, those techniques were not really used by industry professionals, Egyed observed that the main obstacle to wide adoption of inconsistency detection was feedback, which was too slow and of poor quality [28]. To get useful feedback, professionals need it *instantly* and in a *useful* way, i.e. they want to know which model elements are involved in an inconsistency problem. To achieve instant and useful feedback, Egyed uses incremental consistency checking. To find out what the impact of changes are on the model, he compares three solutions: the *"what happens if . . . "* approach, the *type-based scope* approach, and the *instance-based scope* approach. The first one simply asks the question "What happens if this element changes?" The problem is that each change in an element is likely to have impact on a lot of other elements, and it is very hard to identify *all* possible impacted elements. The *type-based* method uses the type of the modified element to find out which other types of elements might be impacted. Finally, the *instance-based* method is similar to the *type-based* method, but instead of working on element types, it works on instances of those elements. The last method is the one chosen by Egyed in his approach. Combined with a profiler that monitors the changes to the model, he can identify very quickly which consistency rules need to be reevaluated after each change. His approach

has been tested on models involving tens-of-thousands of elements and consistency rules, and it was shown to provide "instant" response even on the largest examples.

Later, Egyed et al. built on top of their inconsistency checking method a technique to generate a set of concrete changes to fix those inconsistencies, and providing information about each change's impact on other consistency rules [29]. Instead of using *fixing rules* that, together with the consistency rules, propose possible solutions, Egyed et al., after generating all possible fixes, test them one after the other to determine which ones are actually valid. A valid solution is a solution that actually solves the inconsistency, without introducing a new one. Once again, empirical evidence has shown that, even on very large models, the feedback to the user comes "instantly" [29].

Egyed's approach has two limitations. First, it will only generate potential fixes that do *not* involve the creation of new model elements. Second, it only supports fixes that involve change in only one location.

It would be greatly beneficial to have such a technique for access control properties, as changes in the model, or in the access control properties themselves could also lead to inconsistencies, that could harm the efficiency of the access control model. Just as for UML models in general, incremental detection of inconsistencies would offer professionals a much faster and therefore more interesting feedback on the consequences of their changes in terms of access control.

## 2.2. Access Control

Access control is an old problem, that probably appeared with the development of multi-user operating systems. Concerns have quickly grown over who should be able to access, create or modify resources and data. It became apparent that access to data and processes had to be restricted. In 1985, the US Department of Defense released

the Trusted Computer System Evaluation Criteria (TCSEC) [54], defining two models for access control: Discretionary Access Control (DAC) and Mandatory Access Control (MAC). They are still used today, but have shown their limits, and since then, new models of access control, such as Role-Based Access Control (RBAC) or the more recent Attribute-Based Access Control (ABAC) have been developed to address those limits. This section first highlights the distinction between authentication and authorisation, and then discusses the most important authorisation models.

### 2.2.1. Authentication and Authorisation

Access control is a term that encompasses two complementary yet rather different concepts: authentication and authorisation. The US Committee on National Security Systems (CNSS), in its National Information Assurance Glossary [20], defines authentication as follows:

**Definition 1.** ***Authentication.*** *The process of verifying the identity or other attributes claimed by or assumed of an entity (user, process, or device), or to verify the source and integrity of data.*

It also defines authorisation as follows:

**Definition 2.** ***Authorisation.*** *Access privileges granted to a user, program, or process or the act of granting those privileges.*

Another way of looking at those two concepts is that authentication is the process of making sure that the user is actually who (or the device is actually what) they claim to be, and authorisation is the process that determines whether or not a user (or device) has the access to a resource.

This thesis only discusses authorisation. The models presented are indeed only concerned with authorisation, even though their name may suggest that they also touch on authentication issues.

### 2.2.2. Discretionary Access Control

Discretionary Access Control is one of the access control models defined in 1985 by the TCSEC [54] as *"a means of restricting access to objects based on the identity of subjects and/or groups to which they belong. The controls are discretionary in the sense that a subject with a certain access permission is capable of passing that permission (perhaps indirectly) on to any other subject (unless restrained by mandatory access control)".*

A well known example of DAC is the permission system in UNIX systems, which defines `read`, `write` and `execute` permissions on every file, for its `owner`, its `group` and all the `other` users.

### 2.2.3. Mandatory Access Control

Mandatory Access Control is the other access control model defined by the TCSEC. The TCSEC defines MAC as *"a means of restricting access to objects based on the sensitivity (as represented by a label) of the information contained in the objects and the formal authorisation (i.e., clearance) of subjects to access information of such sensitivity"* [54]. Compared to DAC, MAC is more expressive as it allows the administrator to limit the objects owner's ability to perform some operations. For example, an administrator might want to forbid a range of users from making their files executable.

Multi-Level Security (MLS) [11] can also be achieved with MAC. MLS allows one to define several clearance levels. Each object would get a security level, and only users having a clearance level equal or higher to the object's security level would be able to

perform read operations on said objects, whilst only users having a clearance level lower or equal to the object's security level would be able to perform write operations on said objects.

### 2.2.4. Role-Based Access Control

Role-Based Access Control (RBAC) differs from MAC and DAC as it does not directly assign permissions to users. Instead, it introduces the concept of *roles*. Roles are assigned a set of permissions, and each role can be assigned to as many users as necessary. Permissions in RBAC *cannot* be assigned to users directly. RBAC was first formalised as a general-purpose access control model by Ferraiolo and Kuhn [32], and then refined by Ferraiolo et al. [31]. Later, Sandhu et al. proposed a decomposition of RBAC into 4 different levels, each one adding new features on top of the previous one [92]. The authors then combined their efforts to produce a NIST standard proposal [91], that has since been accepted [72]. Table 2.4 summarises the 4 levels of the standard.

**Table 2.4.:** The 4 levels of the RBAC standard

| Level | Name | Features |
|---|---|---|
| 0 | flat | users, roles, permissions, sessions |
| 1 | hierarchical | role hierarchies |
| 2 | constrained | constraints |
| 3 | symmetric | review |

#### Level 1

Level 1 is called flat RBAC (or RBAC1), and is illustrated in Figure 2.2. The notation used in the figure and the subsequent ones that relate to the RBAC standard comes from the standard. The oval shapes are RBAC elements: users, roles, permissions and

sessions. The arrows represent assignments, and are bidirectional (e.g. a user can be assigned roles, and roles can be assigned to users).

Flat RBAC introduces the basic RBAC concepts, i.e. users, roles, permissions and session. It may look like flat RBAC is equivalent to standard user-group-permission assignments typical of Unix systems, but as the NIST's RBAC FAQ [70] points out, there are two essential differences. First, whilst groups are collections of users, roles are collections of permissions. The distinction is important: indeed, in a classic user-group-permission model, users as well as groups can be assigned permissions directly, whilst in RBAC, they cannot. Second, the concept of sessions is introduced in RBAC and does not exist in a classic user-group-permission model. Sessions allow users to only *activate* a subset of their *assigned* roles, and therefore to only use a subset of the available permissions.

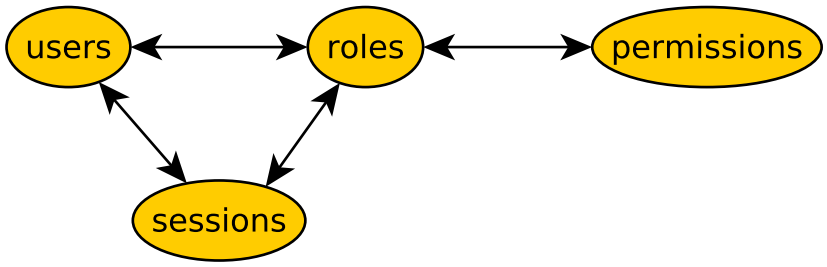



**Figure 2.2.:** Level 1 of the RBAC standard

### Level 2

Level 2 is called hierarchical RBAC, and it introduces role hierarchies on top of flat RBAC, as illustrated in Figure 2.3. The notation is identical to the notation in the previous figure, with the addition of labelled arrows to represent role hierarchies. With level 2, parent-child relationships can be defined between roles. A role will then inherit its ancestors' permissions, and of course any user assigned a role can also use the role's

ancestors' permissions. Level 2 is actually divided in two sub-levels that are carried on in the next levels: level 2a allows for arbitrary hierarchies between roles, whilst level 2b only supports limited hierarchies. What "limited" actually means is not specified by the standard, and it is left to product vendors to specify which limitations are built into their product.

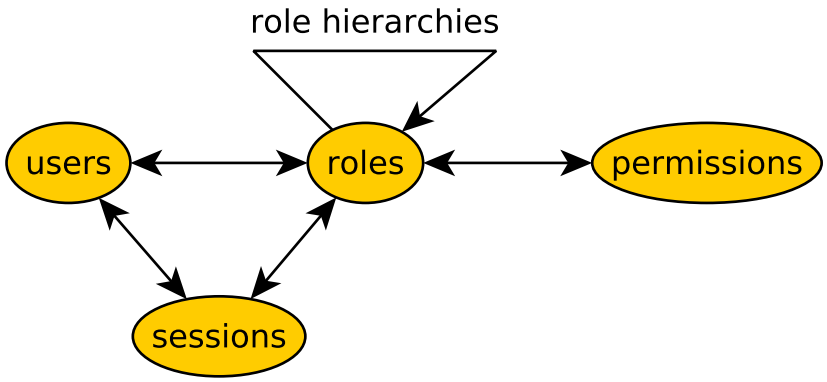



**Figure 2.3.:** Level 2 of the RBAC standard

### Level 3

Level 3 is called constrained RBAC, as illustrated in Figure 2.4. Once again, the notation is identical to the notation in the previous two figures, with the addition of constraints, represented by rectangles, and their application, represented by arrows. Level 3 adds on top of level 2 the ability to express and enforce separation of duty (SoD) constraints. The standard's understanding of separation of duty is closest to Ferraiolo et al.'s work [31], and includes two types of constraints: static separation of duty (SSoD) and dynamic separation of duty (DSoD).

A separation of duty constraint, whether static or dynamic, is a relationship between two roles whose aim is to make sure that users will never be able to acquire too much power through the combination of the permissions assigned to each of those two roles.

Static separation of duty constraints impose rules on user-role *assignments*. If there is an SSoD rule involving roles $A$ and $B$, then users cannot be assigned $A$ *and* $B$. They can be assigned $A$ and not $B$, or $B$ and not $A$, or neither $A$ nor $B$. Formally, SSoD can be expressed as follows:

$$\forall u : user,\ r_{i,j} : roles\ :\ i \neq j :$$
$$u \in roleMembers(r_i) \wedge u \in roleMembers(r_j) \Rightarrow r_i \notin ssod(r_j)$$

where roleMembers($r_i$) denotes the set of users that have been assigned the role $r_i$, and where ssod($r_j$) denotes the set of roles that participate in an SSoD rule with $r_j$ [31].

Dynamic separation of duty constraints are a bit more relaxed, as they do not impose any restriction on role assignments, but only on their *activation*. Indeed, if there is a DSoD rule involving roles $A$ and $B$, then users *can* be assigned both $A$ and $B$, but they cannot *activate* them together. This will prevent users from using the permissions from both $A$ and $B$ *at the same time*. Formally, DSoD can be expressed as follows:

$$\forall s : subject,\ r_{i,j} : roles\ :\ i \neq j :$$
$$r_i \in activeRoles(s) \wedge r_j \in activeRoles(s) \Rightarrow r_i \notin dsod(r_j)$$

where s denotes a subject, i.e. the state of a user at a particular point during a session, where activeRoles($s$) denotes the set of roles activated by $s$, and where dsod($r_j$) denotes the set of roles that particitate in an DSoD rule with $r_j$ [31].

The two types of SoD constraint behave differently in the presence of role hierarchies. With SSoD, two roles cannot be assigned to the same user if two of their ancestors participate in a SSoD rule, as illustrated in Figure 2.5. In the figure, each node whose name starts with $R$ represents a role, whilst the nodes named *U1* represent a user. The white headed arrows between roles represent role hierarchies, and the black headed arrows

between users and roles represent role assignments. The straight lines labelled with *SSoD* represent SSoD rules. With DSoD however, the ancestors' participation in DSoD rules does not prevent simultaneous activation, as illustrated in Figure 2.6. The notation is similar to the previous figure, except that the node named *S1* represents a scenario, the black headed arrows between scenarios and roles represent role activations, and the straight lines labelled with *DSoD* represent DSoD rules. The differences between SSoD and DSoD are due to the fact that, when a role is assigned to a user, its ancestors are assigned too, but when a role is activated by a user, its ancestors are not activated.

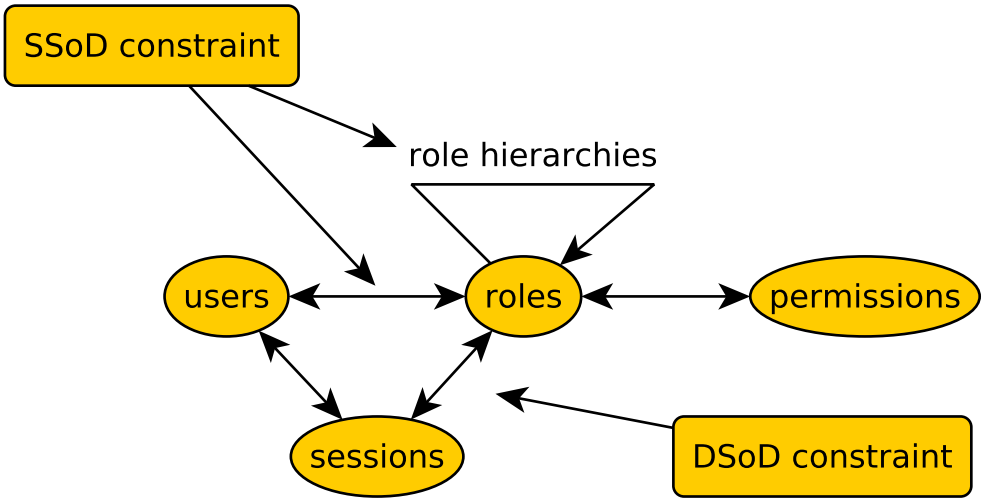
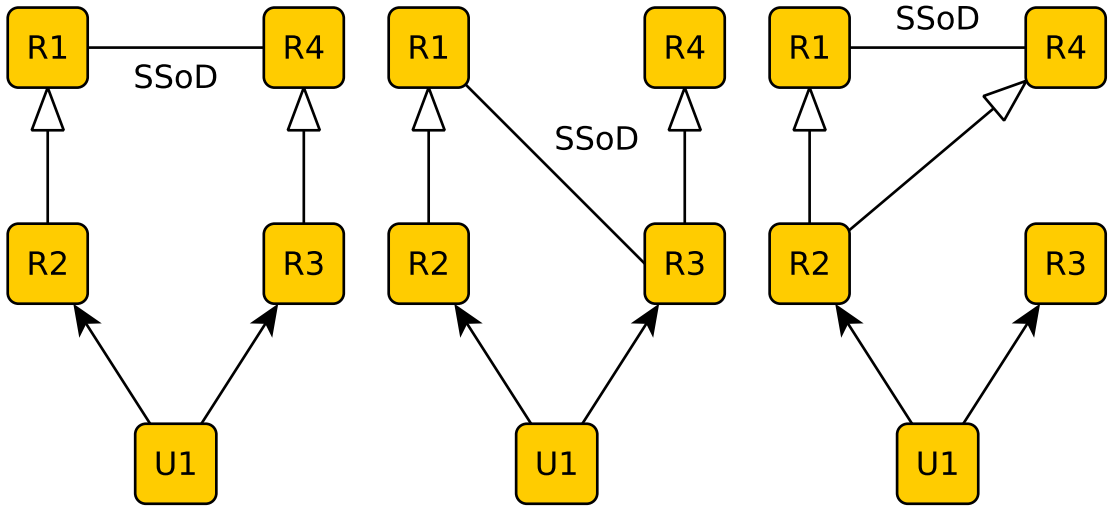



**Figure 2.4.:** Level 3 of the RBAC standard

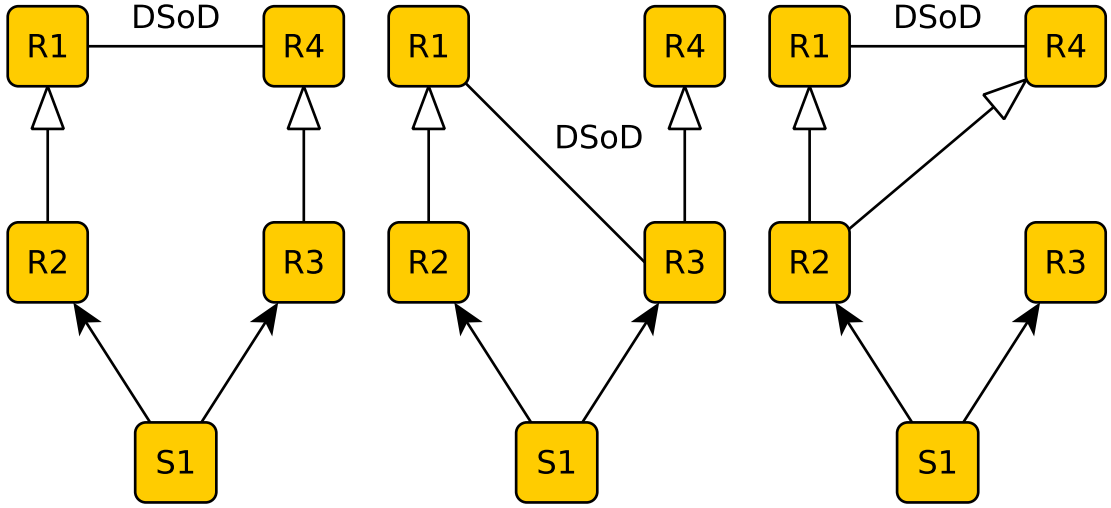
### Level 4

Level 4 is the last level of the RBAC standard, called symmetric RBAC. It is illustrated in Figure 2.7. The notation is the same as the notation for the three previous figures. It adds a permission to role reviewing requirement, in order to help organisations in maintaining their RBAC policies according to the principle of least privilege. The standard defines the permission to role review requirement as follows:




**(a)** SSoD violation **(b)** SSoD violation **(c)** SSoD violation

**Figure 2.5.:** SSoD and role hierarchies




**(a)** DSoD: no violation **(b)** DSoD: no violation **(c)** DSoD: no violation

**Figure 2.6.:** DSoD and role hierarchies

**Definition 3.** *To effectively maintain permission assignments an organization must be provided with the ability to identify and review the assignments of permissions to roles regardless of where they might reside in the organization. When maintaining permission assignments, special attention is taken to abide by the principle of least privilege. [91]*[1]

The principle of least privilege mandates that every program and every user should operate using the least set of privileges required to complete their job [89].

The motivation behind this level of RBAC is to allow system administrators to easily review which roles, and therefore which users, have a specific permission. This can be helpful when dealing with access control policies that have complex role hierarchies. The level 4 requirements allow system administrator to be satisfied that their policy actually behaves as they expect by verifying that a particular user is indeed granted a particular permission.

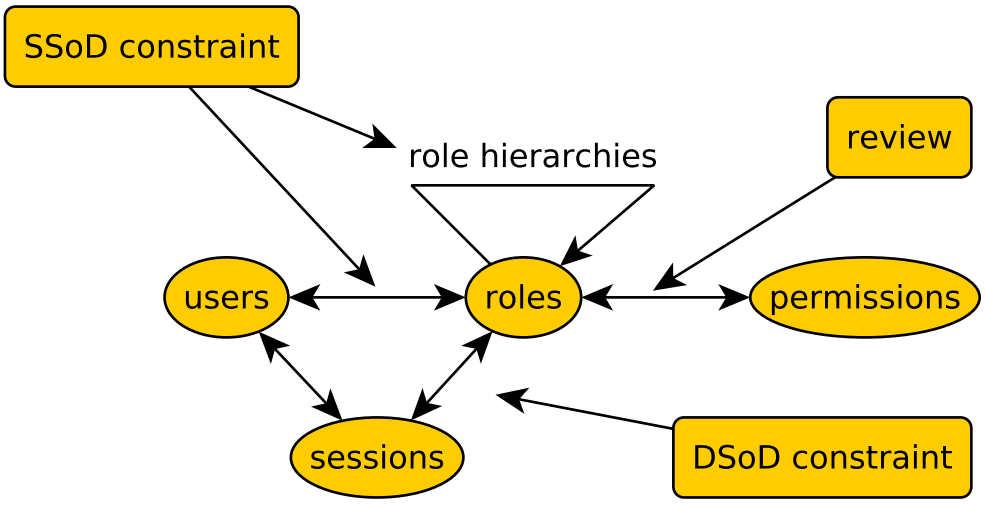



**Figure 2.7.:** Level 4 of the RBAC standard

[1]This quote is reproduced here in its original American English spelling

#### Limitations of RBAC

RBAC is a model for access control configurations that only rely on roles. It is possible to "bend" the roles in RBAC to represent other concepts, such as time. For example, an organisation may only give some permissions during working hours. It can be represented in RBAC by creating new roles for operations that can only be carried on during working hours. Similarly, one can introduce other attributes such as the user's location or the type of connection to the system (i.e. company LAN, internet, VPN, etc.). The problem with this approach is that it quickly increases the number of roles, making them more difficult to manage effectively. Two types of solutions have been proposed to address these shortcomings: extensions of RBAC, and attribute-based access control.

### 2.2.5. Extensions to RBAC

Many extensions of RBAC have been proposed over the years, some of which even before the RBAC standard was finalised. In this section, we briefly describe two of them, to illustrate the extensibility of the RBAC model, and how it has been used as the basis for more expressive models.

#### Organisation-based Access Control

Organisation-based Access Control (OrBAC) was proposed in 2003 by Kalam et al. [51] in order to overcome some of the limitations of RBAC, by considering organisations together with context. The most important entity is the organisation, and it can be seen as *"an organised group of active entities, i.e. subjects, playing some role or other"*. OrBAC also defines other concepts, such as: objects, which are inactive entities; views, which are *"sets of objects that satisfy a common property"*; actions like `read`, `write`, `update`, etc; and activities, which abstract actions in the same way as views abstract

objects and roles abstract subjects. Finally, contexts are circumstances under which certain permissions will be granted.

Security policies in OrBAC allow one to define permissions, obligations, prohibitions and recommendations. To our knowledge, there is not a standardised definition of OrBAC.

#### GEO-RBAC

GEO-RBAC is an extension of the RBAC standard that adds location information to the RBAC standard [24]. Both users and resources can be given a location. The user's location will affect the roles he can activate, while the resource's location will affect the permissions that are required to access it. Interestingly, GEO-RBAC follows the RBAC standard's four-level structure, adding new constructs as required to support their location-aware extension of RBAC. SoD constraints are also extended to allow for the definition of spatial conditions.

### 2.2.6. Attribute-Based Access Control

Attribute-Based Access Control (ABAC) refers to a family of access control models that are inspired by RBAC but more flexible. As Sandhu points out, there is no single, standardised ABAC model [90], but instead several proposals, such as Park and Sandhu's $UNCON_{ABC}$ [82] or Wang et al's logic-based ABAC framework [111].

Where RBAC defines *roles* between users and permissions, ABAC defines *attributes*, that can be required or forbidden in order to give users access to resources. Attributes could be roles of course, but also time, location, or any other criteria used to decide whether or not access to resources should be granted. Typically, an access control rule will specify a series of attributes and their required values to allow for a particular resource

to be accessed. For example, an ABAC rule could state that *all bank clerks can read customers' balance from the branch they work at, between 9am and 4pm on weekdays, and between 9am and 1pm on Saturdays.* The attributes are a role (bank clerks), a location (the branch where the user works), and a time (between 9am and 4pm on weekdays, between 9am and 1pm on Saturdays). The resource whose access is protected is the customers' balance, in read mode. Any user that satisfies the rule will be granted access by the ABAC system, and any user that does not satisfy the rule will be refused access by the ABAC system.

#### XACML

XACML stands for eXtensible Access Control Markup Language[71], a standard for ABAC policies, in XML. Its third version has been standardised by OASIS in January 2013 [71].

### 2.2.7. Access Control Properties Analysis

A lot of research has also been conducted on verifying the conformance of access control policies to some properties or requirements, often using XACML. Fisler et al. propose to transform XACML policies into decision-diagrams to answer queries about said policies, and support evolution of those policies through semantic differencing [34]. Hughes and Bultan take a different approach, as they use a SAT solver to verify properties on XACML policies [45]. Their work is not limited to RBAC, but applies to any policy defined using XACML. Gofman et al. propose RBAC-PAT [36], a tool for analysing RBAC and ARBAC policies. ARBAC is an extension of RBAC that allows one to specify what parts of the policy each administrator is allowed to change. This leads to potentially complex questions about the effects of changes by the administrators. Extending ARBAC

further, Stoller et al. propose Parameterised ARBAC (PARBAC) [106], which supports parameters in order to improve the scalability and applicability of ARBAC policies, and propose an analysis algorithm for PARBAC policies. Dougherty et al. [26] define a framework for reasoning about dynamic access control policies, while focusing on goal reachability and contextual policy containment.

Another access control framework was built around Ponder, a policy specification language developed at Imperial College in London [25]. Ponder2 is its current version, a complete re-write of the Ponder language and its associated framework. The name "Ponder2", just like "Ponder", is used to refer to both the language and the framework built around it [109]. Ponder2 allows one to define access control policies according to an ABAC model. Both obligation policies and authorisation policies can be expressed, as well as constraints on role assignments. Obligation policies are expressed in an Event-Condition-Action manner, to specify the system's response to events under certain conditions. Authorisation policies are defined to specify what a subject can or cannot do on a particular target [25]. Ponder2 is a very complete framework that provides a lot of analysis capabilities such as resolving conflicts in policies [88]. It uses event calculus to formalise and analyse the policy specifications [6].

The approaches described in this section, and the tools that implement them, all work on the artefact level (M0 in the OMG architecture decomposition), while the approach we propose focuses on the model level (M1 in the OMG architecture decomposition). Generally, the approaches described in this section focus on the ability to evaluate various aspects of access control policies, and to verify any property that can be expressed using the language provided. This often means that users need to write queries on the policy, or constraints that the policy should satisfy.

The approach we propose in this dissertation differs not only by the level (M1) at which we operate, but also by the way our users analyse their models. We want to let

them express requirements without having to write constraints or queries themselves, unless they explicitely want to. The consequence is that we have written the constraints ourselves, which necessarily limits the number of constraints that can be evaluated. In other words, we have decided to compromise on the expressiveness in order to lower the technical knowledge requirements, and to tightly integrate our approach with MDE.

## 2.3. Access Control and MDE

Many approaches have been proposed for representing RBAC as part of a Model-Driven Engineering approach.

### 2.3.1. Shin and Ahn's RBAC Representation

Perhaps the first solution for representing RBAC concerns on UML models is Shin and Ahn's representation [97], whose purpose was to *reduce the gap between security models and system developments*. They define three views for representing RBAC models: the *static view*, using class diagrams, to represent users, roles, permissions and sessions, and to define their assignments and hierarchies; the *functional view*, using use case diagrams, to represent functions that the RBAC model should enforce; the *dynamic view*, that refines the functional view by making the interactions between objects explicit.

On top of this extension of the UML meta-model, they define several access control constraints expressed using OCL, such as separation of duty, prerequisite and cardinality constraints [5]. These constraints are model-specific, as they include, for example, the sets of users participating in separation of duty constraints. Therefore, they need to be adapted by the designer to each particular model.

### 2.3.2. UMLsec

UMLsec [48] is an extension of UML 1.4 designed to allow one to express security properties, annotate a UML design, and check the annotated design against said properties. UMLsec uses the standard UML extension mechanisms: stereotypes and tagged values, and provides a tool implementation [3]. Whilst it is not limited to RBAC or even access control, it includes an RBAC profile [48, 62] allowing one to model and verify RBAC concepts on an activity diagram only. Furthermore, UMLsec provides a mechanism that allows one to represent attacker profiles (*profile* here means the capabilities of an attacker, not the UML extension mechanism), but as far as we know, this has not been implemented for the RBAC part of UMLsec, specifically. UMLsec's use of UML 1.x tagged values makes it difficult to use with large models, as all assignments are represented using tuples in a list. Whilst the RBAC profile only covers the first 2 levels of the RBAC standard, related work by Höhn and Jürjens [43] uses Prolog to verify authorisation rules against business requirements, including separation of duty constraints. Their tool supports the SAP system, and can be extended to support other software as well [44]. Another component of UMLsec is related to access control: the analysis of permissions delegations, using class and sequence diagrams [49]. This is however out of the scope of the RBAC standard.

### 2.3.3. SecureUML

Basin et al's research in Model-Driven Security (MDS) [8] has touched on many components of MDE, such as modelling, analysis, model transformation and code generation. The focus here is on the first two aspects. SecureUML [58, 10, 7] is their illustration of MDS. It is a *security modelling language* that can be combined with a *system design modelling language* such as ComponentUML [58], ControllerUML [10, 8] or ActionGUI [9, 8],

using a *dialect* that glues the two languages together, allowing SecureUML to add access control annotations to the system design modelling language. As a consequence, SecureUML can be applied to a large set of models.

The constraints definition and the analysis in SecureUML are interesting: indeed, SecureUML supports analysis through OCL constraints written by the designers, at the model level. With the help of a few handy helper functions, designers can define a large set of authorisation constraints, that go beyond the RBAC standard. They can also write model-level OCL constraints to query the model, therefore providing analysis features only limited by the designer's imagination and technical abilities. However, an OCL constraint is not affected by the existence of another OCL constraint on the model. Therefore, if an analysis query is created, any authorisation constraint that may affect it will have to be integrated in the analysis query, even though it has already been defined elsewhere in the model. On a model with lots of authorisation constraints, this can make analysis queries difficult to write and maintain, and increases the likelihood of errors.

### 2.3.4. Cirit and Buzluca's RBAC Profile

Another proposed UML profile for representing RBAC on UML models is Cirit and Buzluca's [19], which is very similar to SecureUML. On top of the standard RBAC constraints, it also allows one to represent prerequisite roles, time-based constraints and critical permissions, which can be assigned to only one role. The profile allows designer to annotate class diagrams only, and is supported by a list of OCL constraints that ensure the model's well-formedness as well as the enforcement of constraints.

### 2.3.5. RBAC Patterns on UML

Kim et al take a different approach as they suggest to represent RBAC policies as patterns that are later instantiated on a particular model, using UML template diagrams [53]. They also provide the ability to define scenarios and anti-scenarios using object diagrams. The model is then checked against these in order to find potential violations. They also propose to use the same approach to visualise constraints [86] and to detect constraint violations by matching the model against a collection of violation patterns. There does however not seem to be any tool to support their approach, hence it relies on manual inspection of the models, which, especially on large models, can be a time-consuming and error-prone process.

### 2.3.6. Representing RBAC using Aspect-Oriented Modelling

Access Control is an excellent candidate to be implemented using aspect-oriented programming [52], because it is a cross-cutting concern, whose implementation is very likely to be scattered all over the code base. Recognising that this is also the case for RBAC models, Ray et al propose an approach similar to their pattern-based solution [86], where RBAC aspects are created and later woven into the UML model. This allows one to keep the RBAC model separate from the functional model.

Song et al. [103] later expanded the technique to provide support for verifying properties that the model should hold. The weaving process then produces proof obligations that, if verified, ensure that the original property is verified on the target model. The weaving process and the proof obligation creation are, however, manual, which can be time-consuming and error-prone.

### 2.3.7. UML to Alloy

Instead of using OCL queries to find RBAC property violations on UML models, Sun et al. [108] take a different approach and translate the access control policy expressed in UML into an Alloy model that is then analysed using a SAT solver. The analysis tool produces violation traces that are translated back into UML object diagrams for the user to easily identify the issues on the model. They illustrate their approach using LRBAC (Location aware RBAC), an extension of RBAC that adds the concept of location to make decisions about the users' permissions [85]. While models are created using UML, their verification is delegated to Alloy. This requires the development of a mapping between UML and Alloy's format.

### 2.3.8. Constraint-Focused Approaches

#### Sohr et al's Approach

Sohr et al. also propose an UML-based RBAC modelling solution, but they take a different angle from the other solutions discussed in this section. Instead of focusing on modelling access control concerns directly on an application's model, they focus on organisation-wide access control policies and on separation of duty constraints [99]. Their approach allows one to represent the entire RBAC standard, and to express separation of duty constraints in OCL [99]. History-based constraints, e.g. constraints that restrict a user from using a role $A$ after having used another role $B$ in the same session, can be expressed in TOCL, an extension of OCL to support temporal constraints [98], or in LTL [100]. Their tool can validate RBAC policies against the user-defined separation of duty constraints, but it can also identify conflicting constraints and detect missing constraints. The tool can also manage an authorization policy implemented as a web service, where the tool makes sure that only valid changes can be applied to the policy [101].

In follow-up work, Kuhlmann et al provide a complete DSML for RBAC, still with a focus on constraints, and in particular, dynamic, time-based constraints [56]. Their DSML is made of two levels: the policy level, where the usual RBAC elements such as users, roles, permissions and their assignments are represented, as well as the various constraints, on object diagrams; and the user-access level, which defines the scenarios to be checked against the policy level, and are also represented on object diagrams. They developed a tool called OCL2Kodkod to transform the OCL constraints that are used to analyse models into a SAT problem solved by a SAT solver, in order to speed up the verification process. We are, however, not aware of any performance analysis on case studies or examples larger than those presented in their paper.

### OCL for Time Constraints

Access Control models such as RBAC have often been complemented with time constraints, for example to allow some users to activate a specific role only at designated times, or only for a certain amount of time. Li et al propose to implement those constraints using OCL [84]. They define four types of constraints: time span constraints, restricting the period of time during which a role can be activated (e.g. "between 9am and 5pm"); time length constraints, restricting the amount of time during which a role can be activated (e.g. "up to one hour"); time interval constraints, restricting the time interval between two activations (e.g. "the user will not be able to connect within 15 minutes of the termination of his previous session"); average active duration constraints, restricting the average duration of a user session (e.g. "the average duration of a user session between 9am and 5pm will not exceed 10 minutes"). They also combine these constraints with other access control constraints such as separation of duty or prerequisite constraints.

#### Business Processes

Access Control is an important component of business processes modelling, and research has been conducted to model RBAC concerns on UML for business processes. Rodriguez et al propose an extension of UML to express security requirements on activity diagrams [87]. Available requirements include non repudiation, integrity, privacy, access control and others. The requirements are expressed using stereotypes, and have OCL queries attached to enforce them.

Strembeck and Mendling focus their approach on RBAC itself [107] instead of the more general security requirements proposed by Rodriguez et al. They use activity and interaction diagrams to represent RBAC elements as well as constraints such as separation of duty or binding of duty (i.e. a user that has performed a specific task must also perform another one). OCL queries are used to ensure well-formedness of the process model.

### 2.3.9. Discussion

In this chapter we have reviewed the main approaches for modelling access control concerns as part of an MDE approach. While they all propose very interesting ways of representing and analysing access control concerns on models, none of them completely satisfies all the requirements described in the introduction: modelling RBAC, analysis without having to write code or queries, reliance on OMG standards, and automated help for fixing incorrect models.

Shin et al's approach (Section 2.3.1) requires designers to write their own OCL constraints, which is difficult for non-experts, and thus does not fit the "ease of use" requirement. Furthermore, they do not provide a verification mechanism for well-formedness or conformance of the static model to the functional and dynamic views.

UMLsec (Section 2.3.2) provides interesting analysis features, but does not completely support the RBAC standard, as it is limited to level 2. Furthermore, the use of tagged values for the definition of users, roles, permissions and their assignments does not scale with large models. The size of the tagged values will grow with the number of users, roles and permissions, as well as with the number of assignments, quickly making the tagged values difficult to read for humans. Finally, the "ease of use" requirement is somewhat undermined by the limited diagram support, since everything is done on activity diagrams. To extend that support to other diagrams is of course possible with UMLsec, but that, too, makes it only available to expert users, as they will have to implement their own verification routines.

SecureUML (Section 2.3.3) is another excellent approach, but it requires users to write their own OCL constraints, although with the help of handy helper functions. Furthermore, care must be taken when writing analysis constraints, to take into account existing constraints such as SoD, because of the constraint "awareness" problem described in the SecureUML section. Also, the way permissions are represented, using association classes, also makes it difficult to visualise large models.

Cirit and Buzluca's profile (Section 2.3.4) is interesting, but limited to class diagrams, making it difficult to work with other types of UML diagrams, which violates the "ease of use" requirement.

The RBAC patterns approach (Section 2.3.5) relies on manual inspection of models in the absence of tool support, which is error-prone.

The aspect-based approach (Section 2.3.6) is also partially manual, when it comes to the weaving process and the creation of proof obligations.

The UML to Alloy approach (Section 2.3.7) does not fully use OMG standards, which requires an additional step of translating the results to present them to users.

Sohr et al.'s constraint-focused approach (Section 2.3.8) is focused on separation of duty only. It also requires designers to write their own constraints.

Similarly, the OCL for time constraints approach (Section 2.3.8) is also only focused on constraints, and requires designers to write their own constraints.

Finally, the business processes approaches (Section 2.3.8) are obviously focused on business processes, and therefore not generally applicable.

As we can see, no single approach satisfies all our requirements. It is therefore necessary to gather the best ideas out of each approach and to combine them with new developments in order to come up with an answer to the challenge discussed in the introduction.

# Chapter 3.

# Modelling Domain-Specific Concerns

In the previous chapter, we have reviewed existing approaches that integrate access control concerns, and RBAC in particular, with MDE. We have discussed their limitations, and the need for an approach that does not require stakeholders to write code or queries to express their requirements and to verify their access control models against those requirements, as well as allowing designers to model access control concerns on all relevant types of UML diagrams.

Several types of stakeholders are likely to be using an approach that integrates RBAC with MDE: designers and developers of course, but also system administrators, or even decision makers, and others. These groups have varying degrees of technical knowledge, will likely perform varying activities, and will be interested in different types of information. System administrators, for example, will probably only be interested in the RBAC policy itself, i.e. the users, roles, permissions, and their assignments and constraints. Developers, on the other hand, may want to see how the access control restrictions put in place affect the software they are building.

In this chapter, we propose *two* ways of modelling RBAC concerns, both derived from the *same* domain meta-model. The first one is a DSML, which we call `rbacDSML`. It allows stakeholders to model RBAC concepts, independently of any implementation questions. `rbacDSML` is well suited for stakeholders that do not want or need to worry about the impact of the RBAC policy on the implementation of the software, such as system administrators. The second way of modelling RBAC concerns is a DSMAL, which we call `rbacUML`. Instead of looking at RBAC concepts in isolation like `rbacDSML`, `rbacUML` puts these concepts in context by integrating them with the model of the software on which the RBAC policy is applied. This, for example, allows developers to assess the impact of the RBAC policies on the software they are building or maintaining. Since both `rbacDSML` and `rbacUML` are derived from the same meta-model, there are strong similarities between them, as we will see in this chapter.

Using these two modelling languages, a typical workflow could be similar to the following. A company wishes to create a new piece of software that users will have to access, with different access rights depending on complex rules. The company decides to use RBAC to express its access control policy, and chooses our approach for the development and maintenance of their solution. At the start of the project, the system administrators use `rbacDSML` to create their access control policy, and in particular to create and assign roles and permissions, set SoD constraints, and verify that the policy meets their requirements. In parallel, developers and designers use UML to create a detailed model of the software to be built. Once the model is reasonably stable and the RBAC policy has been validated, the designers, developers and system administrators then use `rbacUML` to annotate the UML model with the RBAC policy and requirements that the system administrators have described in `rbacDSML`. This way, developers know which operations in their classes will have their execution restricted to authorised users. The software is developed, and eventually is deployed in production. Then, the system administrators still use `rbacDSML` to maintain the RBAC policy, as users come and go, responsibilities changes, and rules and regulations are updated. At the same time, the designers and developers keep using `rbacUML` to maintain the software and fix the bugs that are reported by the users.

We have implemented both languages using UML profiles. Profiles are UML's extension mechanism, allowing one to define concepts that are not present in the official UML meta-model. The choice of UML was made because it is arguably widely known (although, as Petre's research [83] indicates, it is often used selectively and in a way that is adapted to the context and to the developers' needs), and because the availability of UML modelling and UML profile creation tools allowed us to implement our approach while reusing a lot of existing components. Many other approaches that integrated RBAC into MDE also use UML, such as SecureUML or UMLsec. Of course, `rbacDSML` could have been defined as a brand new DSML using MOF instead of a UML profile. The tool

availability and the ability to reuse existing code ultimately drove our decision to develop a profile for `rbacDSML`. Since `rbacUML` is a DSMAL, i.e. consists of annotations made to an existing model, a UML profile was the only suitable solution.

**DSML vs. DSMAL** Selic makes a distinction between profiles where "it is possible to arbitrarily combine stereotyped elements with non-stereotyped elements in the same model" [95, p.4], and profiles where "modelers may need to limit their models to only those UML concepts allowed by a profile" [95, p.4]. He calls the latter a *strict* application of a profile. His distinction is at the profile application level, i.e. any profile can be strictly applied or not, depending on the modeller's decision. The distinction between strictly applied profiles and not strictly applied profiles will remind the reader of the distinction between `rbacDSML` and `rbacUML`. Indeed, the `rbacDSML` profile is applied strictly, i.e. only `rbacDSML` constructs are allowed on `rbacDSML` models, while `rbacUML` isn't, i.e. other UML constructs are allowed on `rbacUML` models. However, `rbacDSML` and `rbacUML` are *different* languages. This is where we differ slightly from Selic's approach. The reason is that, in `rbacDSML`, we do not want the same concept (e.g. a user) to be represented more than once, whilst in `rbacUML`, we want the same concept to appear wherever it can be useful to the stakeholders using the model. Hence, the profiles have to differ, and the differences between `rbacDSML` and `rbacUML` are more than a decision to strictly apply a profile or not.

**OCL constraints** It this chapter, we use OCL to provide analysis capabilities. We also propose a classification of OCL constraints, define a partial order between those categories, and use it to improve the OCL evaluation speed and the feedback given to the users.

**Why RBAC** We have decided to limit our approach to RBAC models. RBAC is a well-known access control model that has been extensively studied, and has even been standardised. It is therefore very well understood and very well defined. Furthermore, RBAC is the basis on which other access control models expand, such as OrBAC or GEO-RBAC, or even ABAC, as we have discussed in the previous chapter. These models generally *add* new capabilities to RBAC models. Therefore, an approach that works for RBAC is already a step in the right direction and could potentially be extended to support these RBAC extensions. Furthermore, it is always possible to edit the `rbacDSML` and `rbacUML` profiles in order to add the missing constructs and constraints for each access control model. Future work will be focused on ABAC modelling, and will build upon the approach presented here for RBAC.

**Organisation of this Chapter** In the remainder of this chapter, we introduce our approach for modelling RBAC concepts using OMG standards, namely UML, UML profiles, and OCL constraints. We do so by using a sample application for a students marking system, and a workflow that could realistically be applied in a real-life setting: on an existing application, one wants to implement access control to restrict access to some functionalities. We first present our application without any access control considerations, in Section 3.1. Then, we follow Selic's methodology for DSML development using UML profiles [95], in Section 3.2. Since both profiles come from the same meta-model, we first present the meta-model, as well as its associated OCL constraints. We introduce our categorisation of OCL constraints and present the two categories (out of six) that fit into Selic's methodology. We then proceed to describe how we derived the `rbacDSML` profile from the domain meta-model, and show how one can apply `rbacDSML` to create an RBAC policy for our sample application, in Section 3.3. After that, Section 3.4 describes how we derived the `rbacUML` profile from the same domain meta-model, and shows how we can combine the sample application and the `rbacDSML` model into an `rbacUML` model.

After that, we describe the other four categories of OCL constraints, and discuss how one can use the categorisation of OCL constraints to speed up the evaluation of `rbacDSML` and `rbacUML` models, and how it affects the feedback given to users, in Section 3.5. We conclude this chapter with a discussion of the contributions, in Section 3.6.

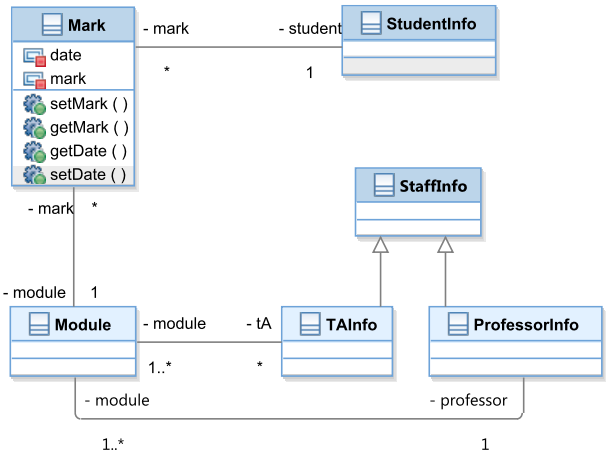
## 3.1. A Sample UML Model

To illustrate our approach, a small UML model is developed for a system that could be used in a university. It is first introduced without any consideration for access control, as per the workflow described below.

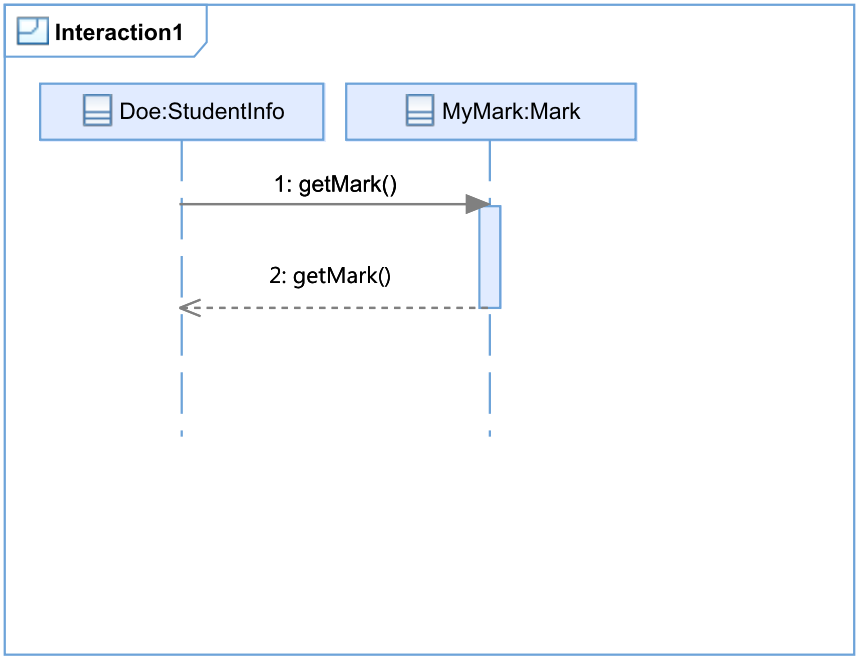
The model allows students' marks to be recorded and accessed. Figure 3.1 shows a class diagram and a simple sequence diagram, using Rational Software Architect's notation. There are small differences between that notation and the standard UML notation used by the OMG, such as the use of icons to represent the operations and attributes' visibility.

The `Mark` class is where the students' marks are recorded. The class `StudentInfo` represents students, and each student can have any number of marks. A mark, however, is always assigned to exactly one student. A mark also relates to exactly one module, represented by the class `Module`, but a module can of course have any number of marks. A module is taught by exactly one professor, represented by the class `ProfessorInfo`. The professor can have any number of teaching assistants to help them, represented by the class `TAInfo`. Of course, a professor can teach several modules, and so can a TA. Both `ProfessorInfo` and `TAInfo` are subclasses of `StaffInfo`, which represents members of staff.

All attributes and methods are hidden to save space and improve readability, except for the `Mark` class since it will be used to introduce access control.




**(a)** Class diagram




**(b)** Sequence diagram

**Figure 3.1.:** Class and sequence diagrams from the sample model

The workflow we will use to illustrate our approach is the following. We start with the above model, that does not contain any access control information. We will then use `rbacDSML` to create a separate model of the access control concepts to be integrated in the software. Then, we will use `rbacUML` to merge the `rbacDSML` model and the UML model. In the end, both the `rbacDSML` and the `rbacUML` models will represent the exact same access control concepts, and the `rbacUML` model will be identical to the original UML model, but with access control information added. We believe that this workflow, which includes the refinement of the `rbacDSML` model into and `rbacUML` model, is quite realistic. It is, after all, related to MDA's distinction between PIM and PSM.

## 3.2. A Methodology for DSML Development Using UML Profiles

Selic's methodology for the development of UML Profiles into DSMLs [95] is made of two parts: first, the construction of the meta-model, carried out in this section; and then, the mapping of the domain meta-model to the actual profile.

### 3.2.1. The Meta-Model

Fig. 3.2 represents the proposed domain meta-model, using MOF. It includes Selic's key elements: the fundamental language constructs, and the set of valid relationships. All the standard RBAC concepts are included, as well as *scenarios*, which are tests that are meant to ensure that the model meets the stakeholders' requirements, and *resources*, to which access is restricted by the use of permissions. Scenarios involve one user, and any number of roles (those, of course, need to have been assigned to the user through user-role associations), in order to access any number of resources, using the permissions

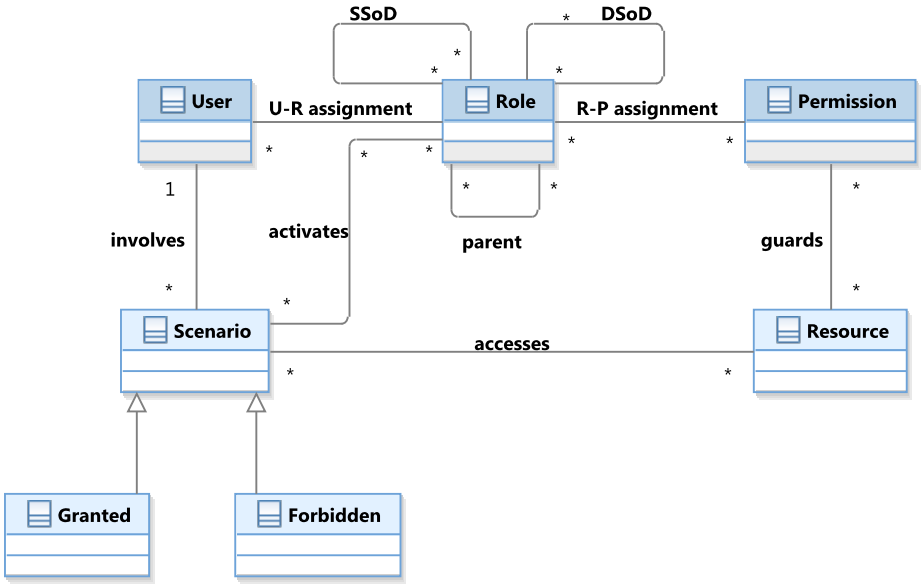



**Figure 3.2.:** The proposed RBAC domain meta-model (using MOF)

given to the user through the roles associated to the scenario. Together, the users, roles, permissions and the associations between them represent the configuration. The resources, together with their permission assignments, form the policy. The scenarios are composed of the scenario elements together with their associations to users, roles and resources. It is the navigability that determines access to resources. For example, a user has access to a resource if there is a navigation path from the user to each of the permissions associated to the resource, through roles and role hierarchies. The activation of roles within a session is done through the scenarios, and in particular the associations between scenarios and roles, named `activates`. A scenario is therefore a snapshot of a particular moment during a session, where a subset of the user's assigned roles are activated.

The concrete syntax of the languages will be derived from UML through the profiles. The semantics of users, roles, permissions, their associations and the constraints and hierarchies are exactly those of the RBAC standard [91]. A user can have any number of roles; a role can have any number of parents, and can participate in any number of SSoD

and DSoD rules. It can also be assigned any number of permissions. Resources can be accessed if and only if the user trying to access them has activated a set of roles that gives them *all* the permissions required to access said resources. Two types of scenarios are defined: in the `Granted` scenario, the user's activated roles must cover the required permissions to access *all* the resources associated to the scenario; in the `Forbidden` scenario, the user, having activated the scenario's roles, must *not* have all the required permissions: at least one resource is inaccessible because of a missing permission. The Forbidden scenarios are called anti-scenarios.

### 3.2.2. OCL Constraints

To specify how the language concepts can be combined, Selic's approach requires a set of constraints that complement the meta-model. He strongly suggests to have them written in OCL, since it was designed to be used with MOF [95]. In this dissertation, we use OCL 2.3, which introduced the transitive closure operator, `closure()`.

There are five constraints that specify how the language concepts may be combined. We discuss them all in this section.

#### Activated Roles and Assigned Roles

In RBAC, users are only allowed to activate roles that have been assigned to them. In other words, the set of active roles for a user at any point in time must be a subset of the set of assigned roles for that user. With our approach, active roles are represented as part of scenarios. Therefore, the OCL constraint to enforce the role activation property is the following:

**Listing 3.1:** Only assigned roles can be activated

```
constraint Scenario inv:
self.user.role->closure(parent)
    ->union(self.user.role)
->includesAll(self.role)
```

### SSoD

If two roles participate in a static separation of duty rule, then no user can be assigned both roles. This can be translated in OCL as the following:

**Listing 3.2:** SSoD constraint

```
constraint User inv:
self.role->closure(parent)
    ->union(self.role)
->exists(role1, role2 | role1.sSoD = role2) = false
```

### DSoD

If two roles participate in a dynamic separation of duty rule, then no user can *activate* both roles at the same time. This can be translated in OCL as the following:

**Listing 3.3:** DSoD constraint

```
constraint Scenario inv:
self.role->exists(role1, role2 | role1.dSoD = role2) = false
```

### Granted Scenarios

We have discussed earlier the Granted scenario requirements: the permissions required to access all the scenario's resources must be provided by the active roles. This can be translated into the following OCL constraint:

**Listing 3.4:** Granted constraint

```
constraint Granted inv:
self.role
->closure(parent).permission
    ->union(self.role.permission)
->includesAll(self.resource.permission)
```

#### Forbidden Scenarios

The Forbidden scenarios are the negation of the Granted scenarios: at least one of the required permissions must be missing. This leads to the following OCL constraint:

**Listing 3.5:** Forbidden constraint

```
constraint Forbidden inv:
self.role
->closure(parent).permission
    ->union(self.role.permission)
->includesAll(self.resource.permission) = false
```

## 3.3. The `rbacDSML` Profile

### 3.3.1. UML Profiles Notation

UML profiles, as we have discussed before, are created by extending the UML meta-model with stereotypes. Stereotypes can have attributes, as well as associations. Stereotypes can be *applied*, or *attached*, to existing UML elements. UML profiles are defined using MOF. However, it is *not* necessary to represent the entire UML meta-model in MOF, together with the constructs introduced by the profile. It is sufficient to only represent those UML meta-model elements that are being extended, and all the others are assumed to be left untouched. For example, Figure 3.3 is the meta-model of the `rbacDSML` profile, discussed

below. The notation used is the following. Stereotypes are annotations on UML elements placed between French quotation marks, such as this: «`Stereotype`». In the figure, the UML meta-model elements that are extended are represented as classes with the «`Metaclass`» stereotype. New stereotypes added by the profile are also represented as classes, but with the «`stereotype`» stereotype. Those classes can have attributes, but no operations. Black-headed arrows represent the extension of a UML metaclass by a profile stereotype. For example, in Figure 3.3, the stereotype `User` extends the metaclass `Class`, which means that the stereotype `User` can be applied on a `Class` element. A stereotype can extend more than one metaclass, and it will then be possible to apply it to several types of UML elements. Blank arrows represent class inheritance, which is valid between stereotypes too. Open arrows, like the arrow between `User` and `rbacRole`, represent associations between stereotypes, or between stereotypes and associations. They have multiplicities, just like normal UML associations.

### 3.3.2. Meta-Model

The `rbacDSML` profile is a DSML derived from the RBAC domain meta-model in Figure 3.2. Once the domain meta-model and its associated constraints have been defined, Selic recommends the following guidelines to derive a UML profile [95]:

1. Select a base UML metaclass whose semantics are closest to the semantics of the domain concept;
2. Check all queries that apply to the selected base metaclass to verify it has no conflicting constraints;
3. Check if any of the attributes of the selected base metaclass need to be refined;
4. Check if the selected base metaclass has no conflicting associations to other metaclasses.

**Table 3.1.:** Correspondence between the meta-model and `rbacDSML` constructs

| Meta-model Concept | UML Metaclass | Stereotype |
|---|---|---|
| User | Class | User |
| Role | Class | rbacRole |
| Permission | Class | Permission |
| Resource | Class | Resource |
| Scenario | Class | Scenario |
| Granted | Class | Granted |
| Forbidden | Class | Forbidden |
| U-R assignment | Association | none |
| SSoD | Association | SSoD |
| DSoD | Association | DSoD |
| parent | Class generalisation | none |
| R-P assignment | Association | none |
| guards | Association | none |
| accesses | Association | none |
| involves | Association | none |
| activates | Association | none |

These guidelines, however, only make sense for what we call in this dissertation a DSMAL, i.e. if one wants to annotate a UML model with domain-specific concepts. In the case of `rbacDSML`, we want instead to create a domain-specific language for the sole purpose of modelling RBAC concerns. Therefore, the choice of base UML metaclasses is not determined by its proximity to the semantics of the domain concept, but instead are based on purely syntactical considerations. For `rbacDSML`, we use UML classes to represent our meta-model elements, and associations between those classes to represent the assignments. Table 3.1 shows, for each element and for each assignment in the meta-model, the chosen metaclass and stereotype in `rbacDSML`. Several assignments do not have a stereotype. This is fine because, since `rbacDSML` is meant for RBAC concepts only, there are no ambiguities for these associations, even without stereotypes - their meaning will be determined by the elements they are attached to. For example, *U-R assignment* is represented by any association between a user and a role, and *guards* is represented by any association between a resource and a permission.

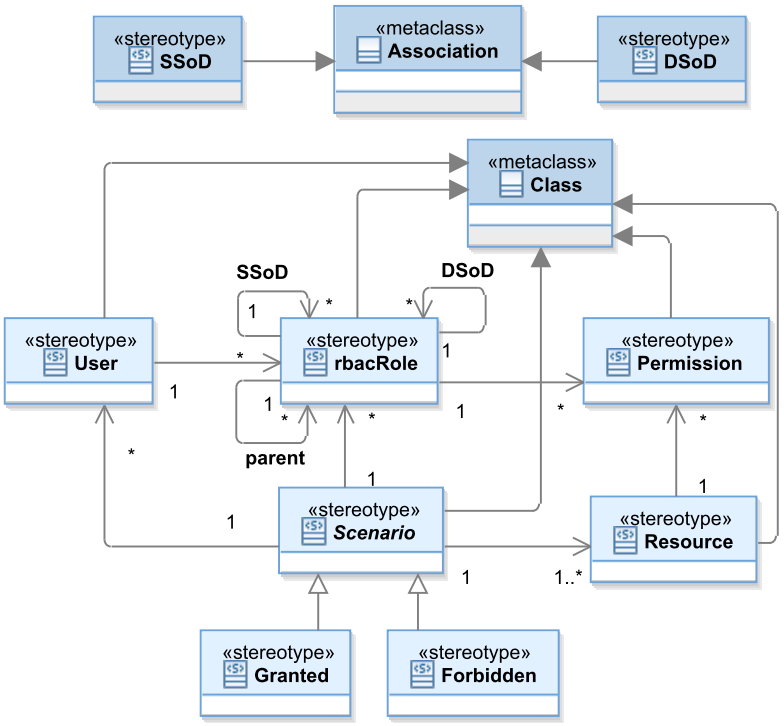



**Figure 3.3.:** DSML meta-model

Figure 3.3 is the `rbacDSML` meta-model. As one can see, it is a direct translation of the domain meta-model to a UML profile meta-model. This is exactly the point of the `rbacDSML` DSML, and will also be reflected in the OCL constraints. One will note that `Role` has been replaced with `rbacRole`. This is because, in UML, role is already used to refer to the name of an association end. To avoid confusion, and errors with the OCL evaluation engine, we therefore renamed `Role` into `rbacRole`.

### 3.3.3. OCL Constraints

Just like the `rbacDSML` profile meta-model is very similar to the domain meta-model, so are the OCL constraints. Indeed, the same number of constraints is provided.

**Roles Activation** The first constraint makes sure that roles activated by a scenario, whether a «`Granted`» or a «`Forbidden`» one, have been assigned to the user associated to said scenario.

**Listing 3.6:** `rbacDSML` roles activation constraint

```
constraint rbacDSML::Scenario inv:
self.user.rbacRole->closure(parent)
    ->union(self.user.rbacRole)
->includesAll(self.rbacRole)
```

**Static Separation of Duty** The second constraint deals with the static separation of duty, and makes sure that no user is assigned two roles that participate in a SSoD relationship.

**Listing 3.7:** `rbacDSML` SSoD constraint

```
constraint rbacDSML::User inv:
self.rbacRole->closure(parent)
    ->union(self.rbacRole)
->exists(role1, role2 | role1.ssod = role2) = false
```

**Dynamic Separation of Duty** The third constraint deals with the dynamic separation of duty, and makes sure that no user activates two roles that participate in a DSoD relationship for the same scenario.

**Listing 3.8:** `rbacDSML` DSoD constraint

```
constraint rbacDSML::Scenario inv:
self.rbacRole->exists(role1, role2 | role1.dsod = role2) = false
```

**Granted** The first verification constraint makes sure that the «`Granted`» scenarios are satisfied by the rest of the model - i.e. that the user who performs the scenario is indeed able to access all the required resources.

**Listing 3.9:** `rbacDSML` Granted constraint

```
constraint rbacDSML::Granted inv:
self.rbacRole
->closure(parent).permission
    ->union(self.rbacRole.permission)
->includesAll(self.resource.permission)
```

**Forbidden** The second verification constraint makes sure that the «`Forbidden`» scenarios are satisfied by the rest of the model - i.e. that the user who performs the scenario is indeed *un*able to access *at least one* of the required resources.

**Listing 3.10:** `rbacDSML` Forbidden constraint

```
constraint rbacDSML::Forbidden inv:
self.rbacRole
->closure(parent).permission
    ->union(self.rbacRole.permission)
->includesAll(self.resource.permission) = false
```

### 3.3.4. RBAC Modelling with `rbacDSML` for the Sample Application

We can now use the `rbacDSML` DSML to define the RBAC policy for the sample application we use to illustrate this chapter. Figure 3.4 shows a possible RBAC policy for the application, with two Granted scenarios, three users, three roles, two permissions, two resources, and one SSoD constraint. On the top left are the users, roles and permissions, and their assignments. On the top right are the two resources that are protected, `Mark_getMark` and `Mark_setMark`. At the bottom are two «`Granted`» scenarios. The

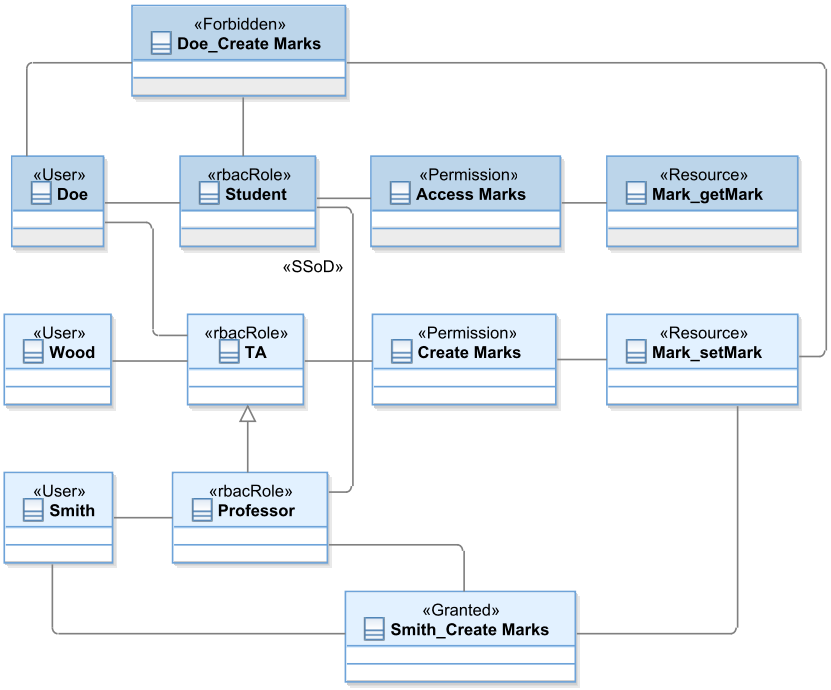



**Figure 3.4.:** Sample model with `rbacDSML`

first one requires that user `Smith`, with the `Professor` role activated, must be able to access the `Mark_setMark` resource. The second one requires that user `Doe`, with the `Student` role activated, must be able to access the `Mark_getMark` resource.

## 3.4. The `rbacUML` Profile

The other profile that we derive from the domain meta-model is `rbacUML`. As opposed to `rbacDSML`, `rbacUML` is what we call a DSMAL, i.e. a language used to annotate a general-purpose model, which is a UML model in this case. Selic's approach applies better for `rbacUML` than it did for `rbacDSML`, since in this case, it actually makes sense to select syntactically close UML elements to match the domain-specific elements. Because the same domain-specific element can sometimes be useful on several types of diagrams,

we have introduced some redundancies in the `rbacUML` meta-model. Indeed, we want access control information to appear in every type of UML diagram where it is relevant.

### 3.4.1. Meta-Model

The result of the application of Selic's methodology for `rbacUML` is the UML meta-model extension on Fig. 3.5. Users, roles and permissions are represented as UML classes (resp. «`RBACUser`», «`RBACRole`» and «`Permission`»). Class inheritance can then be used to represent role hierarchies, and associations can be used to represent user-role assignments, role-permission assignments, static separation of duty (SSoD) and dynamic separation of duty (DSoD) constraints. The resources to be protected are UML operations: indeed, it is convenient to implement access control on their code-level implementation, methods. The call to the access control framework can simply be added at the beginning of the method body to decide whether or not the current user can execute the method. The «`Restricted`» stereotype, therefore, marks operations whose access must be restricted. It also marks messages passed in a sequence diagram, when they are calls to those operations. In the `rbacUML` meta-model, the `Interaction` metaclass represents a UML interaction, perhaps better known under its representation as a sequence diagram. Put simply, an interaction is an ordered sequence of messages exchanged between objects represented with their swimlanes on a sequence diagram.

The scenarios are a bit more complex. Actions (represented as round-cornered rectangles) in activity diagrams are used to represent scenarios (either «`Granted`» or «`Forbidden`»), because they lie in an activity partition (represented as a rectangle with a name, in which actions and other activity diagram element lie) that can represent the user. A partition therefore represents one user («`RBACUser`»), and contains a list of roles that are simultaneously active for that user. That list must, of course, be a subset of the list of roles assigned to the user. These roles are active for all actions within the activity

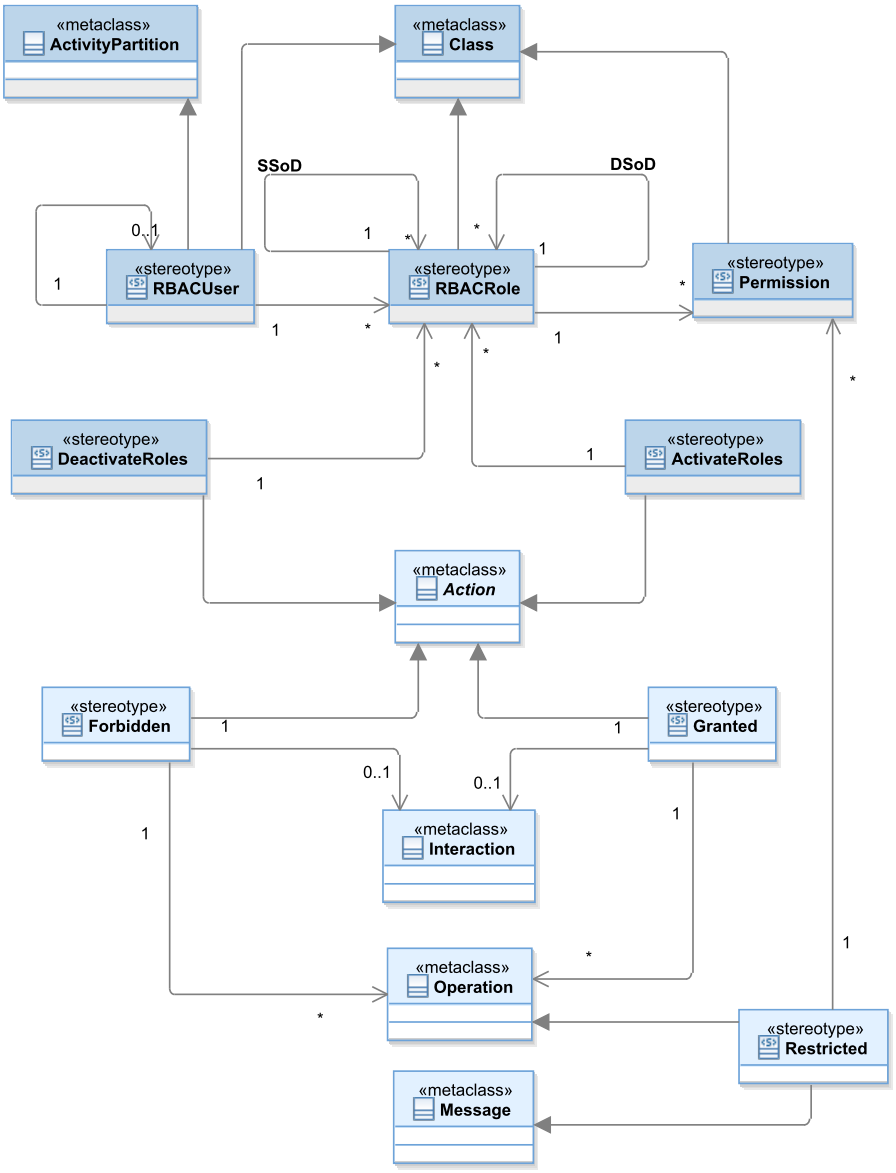



**Figure 3.5.:** Extension of the UML meta-model for access control modelling

partition. Individual actions can have more or fewer roles through «`ActivateRoles`» and «`DeactivateRoles`», to support the activation and deactivation of assigned roles by a user during a session. Finally, actions contain a set of operations, which are the resources for which access by the user must be tested. Table 3.2 shows how each element and assignment of the domain meta-model has been implemented in `rbacUML`.

**Table 3.2.:** Correspondence between the meta-model and `rbacUML` constructs

| Meta-model Concept | UML Metaclass | Stereotype |
|---|---|---|
| User | Class, Activity Partition | RBACUser |
| Role | Class | RBACRole |
| Permission | Class | Permission |
| Resource | Operation, Message | Resticted |
| Scenario | none | none |
| Granted | Action, Interaction | Granted |
| Forbidden | Action, Interaction | Forbidden |
| U-R assignment | Association | none |
| SSoD | Association | SSoD |
| DSoD | Association | DSoD |
| parent | Class generalisation | none |
| R-P assignment | Association | none |
| guards | Association | none |
| accesses | Association | none |
| involves | Association | none |
| activates | Association | ActivateRoles, DeactivateRoles |

**Table 3.3.:** Correspondence between `rbacDSML` and `rbacUML` constructs

| Concept | `rbacDSML` | | `rbacUML` | |
|---|---|---|---|---|
| | stereotype | metaclass | stereotype | metaclass |
| User | «`User`» | Class | «`User`» | Class |
| | | | «`User`» | ActivityPartition |
| Role | «`rbacRole`» | Class | «`rbacRole`» | Class |
| Permission | «`Permission`» | Class | «`Permission`» | Class |
| Resource | «`Resource`» | Class | «`Restricted`» | Operation |
| | | | | Message |
| Granted | «`Granted`» | Class | «`Granted`» | Action |
| Forbidden | «`Forbidden`» | Class | «`Forbidden`» | Action |

Table 3.3 highlights the differences between the stereotype annotations for `rbacDSML` and `rbacUML`. One will immediately notice that the User concept is represented by only one construct in `rbacDSML`, but by two constructs in `rbacUML`. The same goes for the Resource concept, represented by only one construct in `rbacDSML`, but two in `rbacUML`. This is due to the different nature of both profiles. On one hand, `rbacDSML` is a DSML, and as such it needs to be concise and to avoid duplicating the same information in several places. On the other hand, `rbacUML` is a DSMAL, and as such it needs to annotate models with RBAC-related concepts at every appropriate place, even at the price of duplication.

There are a few other differences between `rbacDSML` and `rbacUML` that do not appear in Table 3.3. First, in `rbacUML` only, there are associations between «`User`» stereotypes applied on Classes and «`User`» stereotypes applied on activity diagrams. The same goes between «`Restricted`» stereotypes applied on Operations, and those applied on Messages. Furthermore, the multiple ways of activating roles in `rbacUML` are merged into only one type of association in `rbacDSML`, between the scenario (either «`Granted`» or «`Forbidden`») and the role. This is due to the fact that `rbacDSML` does not handle activity diagrams, whilst `rbacUML` does. The last difference is in the hierarchy relationships between roles. Whilst `rbacUML` uses the Class element's generalisation construct, `rbacDSML` uses a simple association. The reason is, as stated before in this section, that the use of UML by `rbacDSML` is merely a choice of convenience, and that therefore the semantics of UML Classes are ignored.

### 3.4.2. OCL Constraints

The `rbacUML` profile comes with constraints that enforce the same properties as the domain meta-model and `rbacDSML`, and a few additional ones. Indeed, a consequence of allowing one to annotate a UML model with RBAC construct as opposed to allowing one

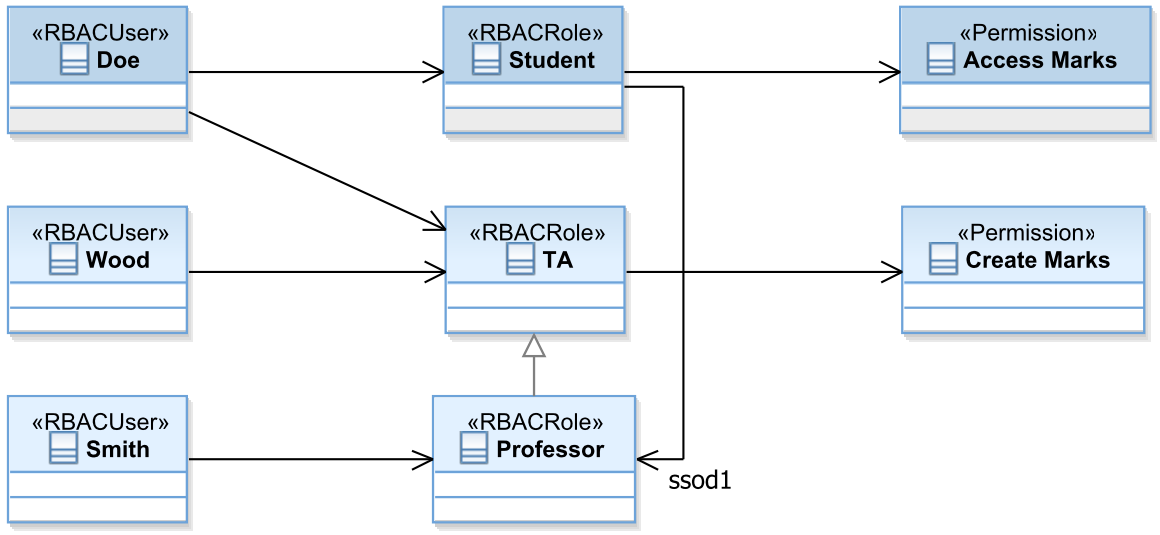



**Figure 3.6.:** Configuration for the sample model

to only build an RBAC model, is that constraints will be more complex. The duplication of the elements also requires additional well-formedness constraints: one needs, for example, to make sure that the name of a user in an activity diagram is identical to its associated user in the access control diagram. There are 32 well-formedness constraints for `rbacUML`, plus the two constraints that verify that the model conforms to the scenarios. In order to keep this chapter concise, we have included all the constraints in Appendices B.1 and B.2.

### 3.4.3. Sample application with `rbacUML`

With `rbacUML` defined, we can now complete the sample application, by applying the last step of the proposed workflow: merging the application model with the `rbacDSML` model, or, to describe it differently, to extend the `rbacDSML` model with the application model. The result is a model made of four types of UML diagrams, with access control annotations that express exactly the same RBAC concepts as the `rbacDSML` model.

By annotating the sample model using the `rbacUML` profile, the configuration (Fig. 3.6) defines 3 users, 3 roles and 2 permissions, their assignments, the role hierarchies and the SoD constraints. `Professor` is a subclass of `TA`, which means it will inherit all of `TA`'s permissions. The SSoD constraint between `Professor` and `Student` means no user can be assigned both roles.

Let us move on to the policy, with the class and sequence diagrams. One will immediately notice that Figure 3.7a includes a few red classes, which are actually part of a *different* diagram discussed earlier: the diagram shown on Figure 3.6. The colour distinction has been added to the figure to clearly show the limit of the class diagram. The reason behind this presentation is that there are associations between two different diagrams. We therefore chose to represent, for each association, the target element on the other diagram.

The resources to protect are the marks: students should be able to read their marks, but only professors and TAs should be able to edit them. The class diagram in Fig. 3.7a is the `rbacUML`-annotated version of the class diagram in Fig. 3.1a. Two operations have been annotated with the «`Restricted`» stereotype: `Mark::setMark()` and `Mark::getMark()`. As one can see, the «`Restricted`» stereotype applied on `Mark::setMark()` is associated to the `Create Marks` permission, which means that the `Create Marks` permission will be required for anyone to execute the `Mark::setMark()` operation. Similarly, the «`Restricted`» stereotype applied on the `Mark::getMark()` operation is associated to the `Access Marks` permission. The sequence diagram on Fig. 3.7b is the same as the diagram of Fig. 3.1b, but the «`Restricted`» stereotype has been added to the message, since it is a call to a method whose access is restricted, `Mark::getMark()`.

One still need to define the scenarios to ensure that the model meets the designer's requirements. This is done with activity diagrams to make sure that a `Professor` can create new marks, and that a `Student` can read them. In the activity diagram of

Fig. 3.8a, each activity partition stereotyped with «RBACUser» represents a user in the access control diagram. Here it has two users: Smith, and Doe. Each user is also given a set of roles that will be active for the whole activity: for Smith, it is Professor, and for Doe, nothing, to illustrate role activation during a session. This means that Smith will have the Professor role active for all the actions performed in the activity (unless specifically deactivated for a particular action), and that Doe will not have any role active. The activity itself is quite simple, and is made of only two actions. First, Smith performs Create Marks, and then Doe reads his marks, using Read Mark. One can see that both actions are stereotyped with «Granted», which means that the users should have the necessary permissions to perform *all* the operations associated to those actions. Only one operation is associated to the Create Marks action: Mark::setMark(), and only one operation is associated to the Read Mark action: Mark::getMark(). Furthermore, the Read Mark action is also stereotyped with «ActivateRoles», which means that the associated roles will be activated for the user on top of those already active. In this case, Doe gets the Student role, on top of his empty list of active roles.

To further illustrate the capabilities of rbacUML, an activity diagram is created to define an anti-scenario: actions that a user should *not* be able to perform. Fig. 3.8b has only one partition, stereotyped with «RBACUser» to represent a user in the access control diagram: Doe. He is assigned the Student role for the whole activity, and there is only one action, Create Mark, stereotyped with «Forbidden», which means that Doe, with his set of active roles, should *not* be able to perform all the corresponding operations. The action is associated to only one operation, Mark::setMark().

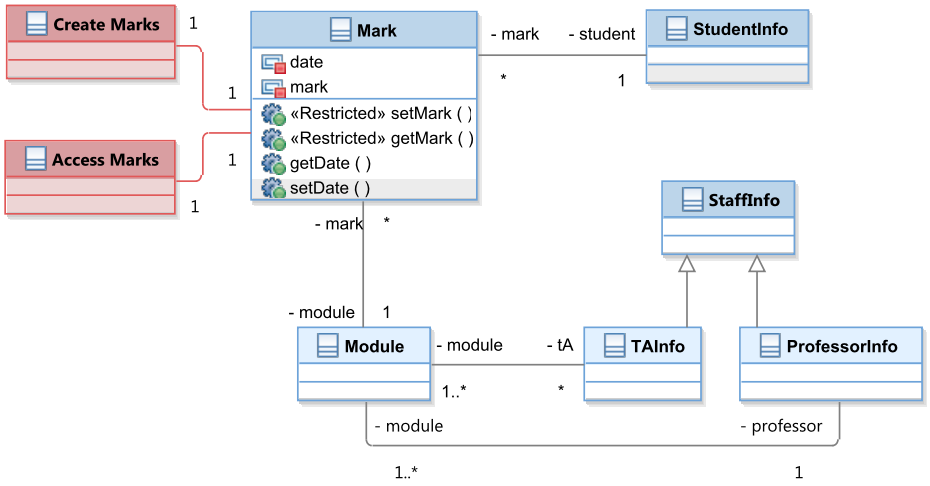
One can now verify whether the model enforces the scenarios: in order to be able to perform the Create Marks action, Smith must be able to perform the Mark::setMark() operation, which requires the Create Marks permission. Smith has the Professor role active, which gives him, through its hierarchical relationship with the TA role, the Create

`Marks` permission. The model thus enforces the first scenario. Similarly, the second scenario, `Read mark`, requires `Doe` to be able to execute the `Mark::getMark()` operation, which requires the `Access Marks` permission: through the `Student` role he has activated especially for that action, he gets the `Access Marks` permission, and the model enforces the second scenario. The anti-scenario requires that `Doe`, with the `Student` role, must not be able to perform the `Create Mark` action, which is associated to the `Mark::setMark()`. As seen before, that operation requires the `Create Marks` permission, which is *not* available through the `Student` role. Therefore, `Doe` cannot perform the `Create Mark` action, and the anti-scenario is enforced.

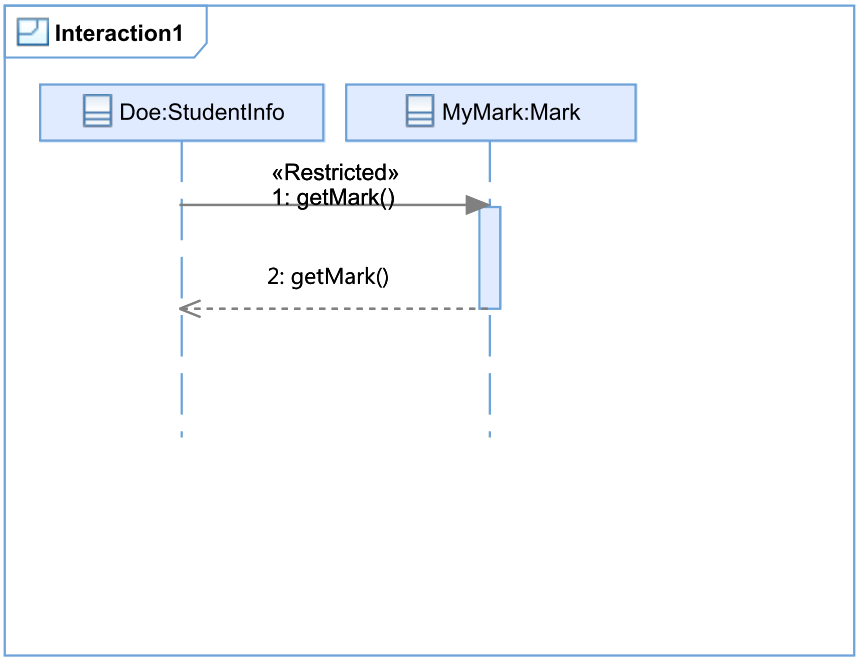
## 3.5. A Taxonomy of OCL Constraints

We have presented earlier several OCL constraints, whose purpose was to complement the proposed meta-models in order to describe how the languages' constructs could be combined. In this section, we propose more types of constraints, as well as a categorisation of all the constraints in six categories. In this section, we focus on `rbacUML`, but of course, the taxonomy presented here also applies to `rbacDSML`, and the constraints could easily be translated to `rbacDSML` as well, since `rbacUML` is essentially a refinement of `rbacDSML`.

Selic only mentions one kind of OCL query: well-formedness queries that, together with the extension of the meta-model, form the DSMAL's abstract syntax. Here, however, further support is provided for designers to find out what has not been modelled and detect redundant elements. Besides the definition of an annotations language with its syntax and semantics (enforced by well-formedness and verification OCL constraints), the `rbacUML` profile provides further modelling support, with OCL constraints to check the completeness, coverage and redundancy of the configuration and policy, and the satisfiability of the scenarios. All these queries are implemented as part of the `rbacUML`

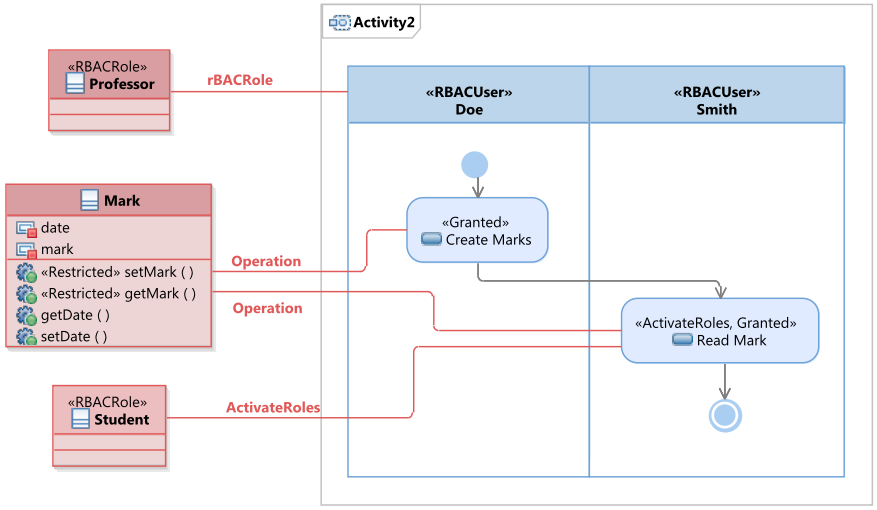



**(a)** Class diagram

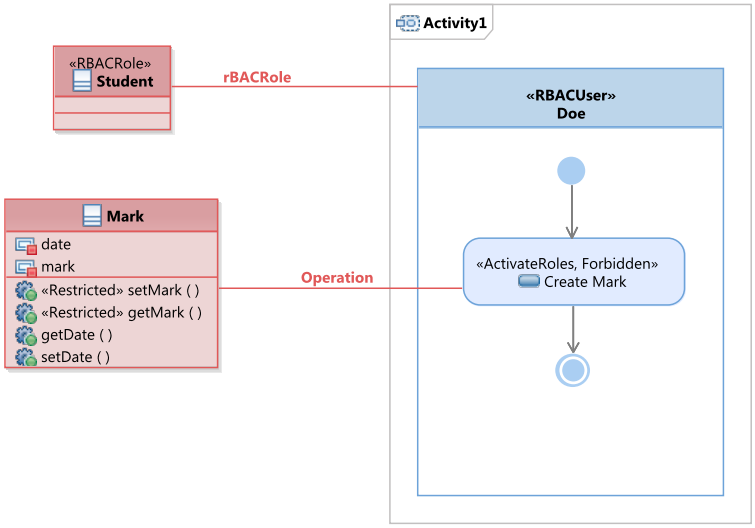



**(b)** Sequence diagram

**Figure 3.7.:** Policy for the sample model




**(a)** Scenario




**(b)** Anti-scenario

**Figure 3.8.:** Scenarios for the sample model

**Table 3.4.:** Summary of severity and type of OCL queries for each category

| | well-formedness | verification | satisfiability | coverage | completeness | redundancy |
|---|---|---|---|---|---|---|
| severity | error | error | warning | warning | warning | warning |
| type | constraint | constraint | query | query | query | query |

profile, which means that they are hidden from the designers, who will *not* have to write OCL queries themselves for the particular models they work on using the profile. Instead, they can run the profile queries automatically, and will get feedback if their evaluation fails.

This section proposes a taxonomy of OCL queries for profiles and describes each disjoint category. These categories are guidelines to make sure that no queries have been forgotten, and they complement Selic's work, since they are not limited to the definition of a DSMAL. Each category is illustrated by `rbacUML`, indicating how to systematically check that no queries have been forgotten. Each category of OCL queries also receives a severity level, either *error* or *warning*. This is because violations of some categories of queries do not necessarily make a model incorrect. As a general rule, a query should always be broken down into smaller queries if possible, making it easier to diagnose what the problem is when a query is violated. Table 3.4 summarises the categories of OCL queries, their severity level and their type, which can be either a constraint returning a boolean or a query returning model elements.

### 3.5.1. Well-formedness

Well-formedness is the first category of OCL queries. It is similar to Egyed's UML consistency [28] as discussed in Chapter 2. We focus only on the well-formedness of the annotations added by the profile. The goal is to ensure that the profile annotations that define the access control specification on the model are syntactically correct. These

queries are expressed on the configuration, the policy and the scenarios: they must consider the entire profile to be effective. The rules include well-formedness (some well-formedness rules described by Selic [95] correspond to Egyed's consistency rules [28]) between different stereotypes, elements and/or associations. For example, one may want to make sure that if a class element is stereotyped with A, then it cannot be stereotyped with B, and vice-versa. Well-formedness queries are the first ones to be defined during the profile development process, since all the other categories assume a well-formed model with regard to the UML profile. Well-formedness queries are always constraints.

To make sure that no constraint has been forgotten, profile developers should pay particular attention to the following:

**1)** if two stereotypes, or the same stereotype applied on different UML elements, represent the same domain concept or requirement, well-formedness constraints are likely to be necessary to enforce that both the elements on which the stereotypes are applied share some common characteristics, e.g. having the same name. For example, Section B.1.27 of the appendix shows a constraint that makes sure that the name of an activity partition on which the «`RBACUser`» is applied is the same as the name of the class on which the «`RBACUser`» is applied and that is linked to the activity partition using an association;

**2)** if a stereotype can be applied to more than one type of UML element, multiplicities in the meta-model may not be correctly enforced, and should therefore be completed with well-formedness constraints. For example, Section B.1.26 of the appendix shows a constraint that makes sure that, if the «`RBACUser`» stereotype is applied on a class, then there is no *alias* association from that stereotype. Another constraint, in Section B.1.25 of the appendix, makes sure that if the same stereotype is applied on an activity partition, then there is exactly one *alias* association from that stereotype. This cannot be enforced using the meta-model alone, and therefore, OCL constraints are required;

**3)** in the case of indirect associations, one may have to check indirect multiplicities and enforce them through well-formedness constraints, when the indirect multiplicity must be more restrictive than what the meta-model allows to model through direct multiplicities. There is no example of such a constraint in `rbacUML`, but the following scenario can be considered to illustrate this point: if the number of permissions that each user can get is limited to $N$, then one would have to write an OCL constraint that will, for each user, build the set of roles assigned to them. Then, for each role assigned to the user, the constraint would build the set of permissions assigned to the role. Finally, the constraint would merge all the sets of permissions, eliminate duplicates, and make sure that the size of the set is not larger than $N$.

In total, `rbacUML` has 32 well-formedness constraints, listed in Appendix B.1.

### 3.5.2. Verification

Verification, according to the Capability Maturity Model (CMMI) [2], is "the process of evaluating software during or at the end of the development process to determine whether it satisfies specified requirements". If the DSMAL meta-model allows to express scenarios, they must be verifiable.

Having specified well-formedness rules will guide the profile developer to implement the verification queries, which are typically more complex than well-formedness constraints, and the failure in the evaluation of an instance of such a query must raise an error that designers have to resolve. Like with the well-formedness queries, verification queries are actually constraints: either they succeed and the configuration and the policy satisfy the access control requirements, or they fail and they don't satisfy the access control requirements.

In `rbacUML`, one has two types of scenarios: a user should, or should *not*, be able to perform a series of operations with a set of activated roles. Each scenario is an action, stereotyped with either «`Granted`» or «`Forbidden`», within a specific activity partition representing a user, and given a set of active roles that are a subset of the roles assigned to said user. Two verification constraints (Appendix B.2) are derived to check whether the configuration and policy enforce the scenarios: the first one verifies that «`Granted`» actions can be performed by the user with the activated roles, and the second one verifies that «`Forbidden`» actions cannot be performed by the user with the activated roles. The first one constructs two sets of permissions: the set of permissions *required* by the operations that are part of the considered action, and the set of permissions that the user has, through the roles s/he has activated. The former set must be a subset of the latter. The verification constraint for «`Forbidden`» actions works in a similar way, but the former set must *not* be a subset of the latter, i.e. there must be at least one permission that is required but that the user does not have.

### 3.5.3. Satisfiability

Satisfiability queries are related to verification queries. Satisfiability queries help answering the following question: when a scenario is not enforced by the model, is there a particular element that will *always* make the scenario fail? For example, an operation stereotyped with «`Restricted`» could require more permissions than any user has, or an action could require more permissions than the user that runs it could get. The evaluation of satisfiability queries only makes sense if a verification constraint has failed, and therefore satisfiability queries should be developed after verification constraints. Satisfiability here is similar to the concept of satisfiability in logic, where a formula is satisfiable if there is at least one interpretation that verifies it. In `rbacUML`, a scenario will be satisfiable if

there is at least one user that can execute it, and an anti-scenario will be satisfiable in there is at least one user that *cannot* execute it.

In `rbacUML`, 3 satisfiability queries are specified (Appendix B.3) to help one identify where the problem lies in case one of the verification constraints is violated.

### 3.5.4. Completeness

A completeness query identifies areas where elements or annotations are missing, either intentionally (modelling *everything* does not always make sense) or not (it is then useful to point out where something is missing). A completeness problem does not mean that the model is not correct, so the severity level is *warning*. Completeness queries deal with the configuration and the policy, but not the scenarios, as those are dealt with by coverage constraints (see below).

To find all the possible completeness queries, the associations in the profile must be considered. If an association has a multiplicity of `0..x`, where `x` could be any integer or `*`, then a completeness query is needed: not having any association there might be intentional, but it may also be a mistake.

In `rbacUML`, 5 completeness queries are defined in Section B.4 of the appendix.

### 3.5.5. Coverage

Coverage queries are a kind of completeness queries, but focused on scenarios. As with the completeness queries, just because scenarios do not cover the entire model does not mean that the model is incorrect. Therefore, the appropriate severity level is *warning*. In software testing, coverage measures the amount of source code that has been tested. There are several coverage criteria, like the blocks covered, decisions executed or variables

used [35]. In the context of access control, scenarios can be seen as the tests of the configuration and policy. The definition of coverage is adapted to the context of profile development: coverage becomes therefore *a measure of the degree to which a policy and a configuration are covered by the scenarios*. Indeed, some parts of the policy or the configuration may not be involved in the verification of any scenarios. This is not necessarily bad, as it would usually be overly time-consuming to model scenarios to cover the entire model, but it is still important to know which areas of the policy and configuration are covered by scenarios, and which areas are not. Coverage queries assume that the model and the profile annotations are consistent. Therefore they should be defined after the well-formedness constraints have been developed. Furthermore, the result of the coverage analysis will only be meaningful if the well-formedness queries succeed.

In `rbacUML`, scenarios (resp. anti-scenarios) are defined as actions that represent a set of operations that a user must (resp. must not) be able to perform using a given subset of the roles assigned to them. In Section 3.4.3, we have 3 users, 3 roles, and 2 operations. In order to cover all possible combinations, one should have at least 72 ($= users \times (\wp(Operations) - 1) \times \wp(Roles) = 3 \times 3 \times 8$) scenarios to reach complete coverage. Clearly, one cannot model all possible scenarios, especially on large models.

In order to make sure that no coverage queries are missed, one needs to looks at each verification constraint, and see which stereotyped elements are visited through associations. Those elements, if they exist but are not visited, should raise a coverage warning.

In `rbacUML`, 2 coverage queries are identified and detailed in Section B.5 of the appendix. Both the «`Granted`» and the «`Forbidden`» verification constraints visit the same elements: «`Users`», «`Roles`», «`Permissions`» and «`Restricted`» operations. The

coverage queries check which of those model elements are not visited by the verification constraints.

### 3.5.6. Redundancy

Redundancy appears when the same concept instance is repeated in the model, i.e. removing one of them will not affect the evaluation of any of the OCL queries in the profile. Redundant elements increase the number of elements in the models, which increases the time necessary to evaluate all the OCL queries and makes the model more difficult to understand. Redundancies should therefore be eliminated. A redundancy query is used to find such redundancies, allowing the designer to safely delete one of the redundant elements, after making sure that the associations pointing to said element are redirected to the redundant element that will not be deleted, if appropriate. For example, in `rbacUML`, if two users, `A` and `B`, are found to be redundant, then one of them can be deleted. If `A` is to be deleted but an activity partition stereotyped with «`User`» refers to `A`, then this association must be transferred to `B` and the activity partition's name must be changed to `B`. For the example in Section 3.4.3, if one finds out that two users are redundant and remove one, the number of necessary scenarios to achieve full coverage is reduced from 72 to 48.

Redundancy applies to the configuration only. It does not make sense on the policy, since two operations are never exactly the same, nor does it on the scenarios: if the same action appears in several places in an activity diagram, or even in several activity diagrams, this is because of the functional requirements expressed by said diagrams. Therefore, redundancies should not be removed. The configuration, however, should be kept as small as possible.

Just as with coverage and completeness queries, redundant elements do not make the model incorrect, and therefore redundancy queries have a severity level of *warning*. Yet, it is recommended to eliminate redundancy as soon as possible.

With `rbacUML`, 2 redundancy queries are specified in Section B.6 of the appendix.

### 3.5.7. User-Defined Queries

In addition to the queries provided by `rbacUML`, users can of course define their own. This can be useful in several cases. A user could be using a particular authorisation library that enforces constraints that are not part of the RBAC standard. One such constraint could be that any role can only have one parent, or that dynamic separation of duty is not implemented. Designers may also want to provide their own constraints if they want to perform different types of scenarios in the verification category. For example, one may want to design a scenario that makes sure that a "default" user does not have more roles than any other user, or that any user with a specific role also has another one. Since one uses standard UML technologies, adding a new query or updating an existing one only requires the designer to edit the relevant OCL queries in the rbacUML profile, which will be trivial for someone familiar with UML and OCL. If the new query is added to a particular category, the ordered and selective evaluation strategies will be applied automatically.

### 3.5.8. Evaluation of OCL Queries

UML modelling tools typically evaluate *all* OCL queries on an entire model when the validation is triggered, which can cause several problems, especially on large models:

- it takes a *long* time to evaluate all those queries;

- when many errors arise, it is hard to make sense of the output and to know where to start;
- the result of the evaluation of some queries is only useful if other queries have been validated, otherwise meaningless results are scattered over the output, making the above point worse;
- the developer might not always be interested in all the categories of queries.

This section presents two evaluation strategies to increase the performance of OCL queries: ordered evaluation and selective evaluation. They can be used individually or combined together. Their performance is discussed in Chapter 5.

### Ordered Evaluation

Dependencies between the categories of queries listed previously have been identified. In other words, for the result of the evaluation of queries from a particular category to make sense, the evaluation of the queries from the categories it depends on must have succeeded. For example, `rbacUML` has a well-formedness constraint that says that roles activated by a user in an activity partition must also be assigned to the corresponding user in the configuration. One can imagine a scenario where this query fails: there is at least one activated role that the user actually does not have. Now, imagine that inside the activity partition, there is a «`Granted`» action, and that one of the related operations requires a permission that is *only* provided by the role that is activated but not assigned to the user. The verification query will evaluate to *true*, but that result is meaningless since there is an active role that the user cannot actually have. This leads the designer to mistakenly think that the model is more secure than it actually is. Moreover, checking all constraints simultaneously may overwhelm the user with useless information, hiding important results in a sea of meaningless ones.

Ordering the evaluation of OCL queries brings several benefits:

1. fewer meaningless results;
2. potentially reduced evaluation time, especially when errors are caught early on;
3. possibility of selectively evaluating some categories: for example, one may want to evaluate verification and completeness queries only, not being interested in coverage and redundancy queries.

We call this approach ordered OCL query evaluation, as it has similarities with the ordered evaluation of boolean expressions in some programming languages.

#### Selective Evaluation

As opposed to ordered evaluation that automatically skips the evaluation of queries whose result would be meaningless because of the result of other queries further up the dependency graph, query selection allows the designer to manually select which queries, or categories of queries, to evaluate at a particular time. For example, a designer might only be interested in well-formedness queries at some point because he has not given much thought about the scenarios yet, and therefore it is pointless to run verification queries. He can then select the well-formedness category only, and only those queries will be evaluated, no matter what the result of the evaluation is. Similarly, at a later stage the designer may only be interested in a particular coverage query, that reports roles that have not been assigned to any user. He can select it and deselect all the other ones, so no time will be spent on evaluating other coverage queries such as the query that finds permissions that have not been assigned to any role. This is also a way of coping with too many errors or warnings resulting from the evaluation of queries that the designer is not interested in at a particular moment.

## 3.6. Discussion

This chapter has presented the `rbacUML` DSMAL and the `rbacDSML` DSML, both derived from the same domain meta-model using Selic's methodology. Both profiles provide a fully standard-compliant RBAC language, as well as the ability to model two types of scenarios to check the model against access control requirements. We have illustrated our approach using an example application and a workflow that makes use of both profiles.

The `rbacUML` profile targets users, such as developers, that need to understand the details of how the access control policy and configuration interacts with the software to be built. Therefore, the relevant model elements can be annotated with RBAC concepts. This introduces necessary redundancy, because UML elements themselves can be redundant.

The `rbacDSML` profile, however, targets users that only need to focus on the access control part of the system, e.g. system administrators or stakeholders without a programming background. The DSML is much smaller and comes with significantly fewer OCL constraints, which necessarily decreases its validation time.

A categorisation of OCL constraints is used later to provide two ways of speeding up the validation of a model and improving the quality of its feedback.

If the proposed approach were to be re-framed in Basin's Model-Driven Security framework, `rbacDSML` would be the security modelling language, UML the system design modelling language, and the combination of both would be `rbacUML`.

Compared to the other approaches for RBAC modelling presented in Chapter 2, this proposal is closest to UMLsec and SecureUML. The scenarios here will remind the reader of UMLsec's activity diagrams, but instead of using tagged values to represent lists of users, roles, permissions and their respective assignments, classes, operations and associations

are used. This is an improvement over UMLsec's representation, as its lists of assignments (e.g., for a simple user - role assignment: `{(user1, role1), (user1, role3), (user2, role2), (user2, role3), (user2, role4), (user3, role1)}`) grow very quickly and are therefore difficult for humans to parse. Using classes, operations and associations is both clearer and more concise.

The proposed approach also has similarities with SecureUML + ComponentUML: both use classes to represent users and roles, and resources to be protected are represented in similar ways. However, the similarities stop there: whilst SecureUML represents permissions as association classes attached to role-resource assignments, `rbacUML` uses classes, which allows for the same permission to be reused across multiple roles and resources. Since SecureUML uses association classes and since the UML standard mandates that an association class can only be attached to *one* association, a permission will have to be repeated for each role to resource assignment. The way SoD constraints are represented is also different: SecureUML uses model-level, user-defined OCL constraints, whilst `rbacUML` uses associations between roles. Similarly, SecureUML allows users to define themselves model-level OCL constraints for analysis purposes, while `rbacUML` uses actions in activity diagrams to represent them, and meta-model-level OCL constraints, that users do *not* need to write themselves, to perform the analysis itself. SecureUML, however, is more flexible in the sense that users are able to express more complex constraints than using the proposed approach. This comes at the cost of added complexity.

The proposed approach for RBAC modelling meets the requirements set out in the introduction:

**Modelling RBAC concerns** RBAC concepts can be modelled by stakeholders. All the RBAC concepts, as well as the scenarios, can be modelled using either of the proposed

profiles. There is no requirement for stakeholders to write any code or OCL constraint themselves. Both profiles also support the entire RBAC standard.

**Analysing models** Once they have created their RBAC models and requirements, stakeholders are allowed to analyse said models in one click. The OCL constraints that implement these analysis features are written at the meta-model level and are part of the profile.

**Classification of OCL constraints and evaluation speed improvements** We provide a classification of OCL constraints in six categories: well-formedness, verification, satisfiability, completeness, coverage, and redundancy. These categories provide a range of analysis capabilities. Using this classification, we define a partial order between categories, allowing us to only evaluate constraints when it makes sense to do so. Therefore, the number of constraints to evaluate can sometimes be reduced, but is never increased. This can lead to faster evaluation times. We also provide users with the ability to manually select which categories of constraints to evaluate, which can also reduce the evaluation time.

**Fewer useless results in the evaluation feedback** The partial order between constraints relies on assumptions made during the constraints creation, e.g. verification constraints assume that the model is well-formed. The ordered evaluation allows us to only evaluate constraints if such assumptions are met. Not only does this reduce the evaluation time, as discussed above, it also removes any feedback on constraints whose assumptions have not been met, and whose results are therefore meaningless.

# Chapter 4.

# Fixing Models

It is not uncommon for the evaluation of `rbacDSML` or `rbacUML` models to fail. In fact, this is true of models in any similar DSML or DSMAL. Especially with large models, small errors can easily go unnoticed until the evaluation of the OCL constraints points them out. Furthermore, the very nature of the evaluation engine, where model elements must satisfy several constraints, makes it rather difficult for designers to manually fix erroneous models. A change that fixes an error on one instance of an OCL constraint can result in other instances of the same, or even other, OCL constraints, to raise new errors that were not there in the first place. These errors will then have to be fixed, potentially causing more errors elsewhere, until a model that satisfies all instances of all constraints is produced.

Moreover, by manually fixing their models, designers are likely to overlook or "miss" possible changes, which would lead them to select a suboptimal or overly complicated solution to their problem.

Automatically generating a list of valid models that can be derived from an incorrect one would address these two problems. It would make the designer's life much easier, as he would only have to review several correct alternatives, and choose the one that suits him best. It would also present him with the options he may not have considered had he tried to manually fix the model.

In this chapter, a graph-based solution for the correction of erroneous models is presented, discussed and evaluated, under several angles such as completeness, correctness, and performance. A reference implementation for `rbacDSML` is also discussed.

## 4.1. Overview of the Solution

To fix a model is to fix each of the errors raised during its evaluation. However, fixing an error may introduce another error somewhere else. Furthermore, there usually are

several ways of fixing a particular error, and therefore, several ways of fixing the entire model. In this chapter, the fixing of individual errors is first considered, regardless of whether or not a particular fix causes other errors elsewhere on the model.

In `rbacDSML`, errors can be classified in three categories that will be described in this chapter, and expressed using graph theory. For each instance of a constraint that needs to be verified, a graph can be constructed using the elements and associations that are navigated during the instance's evaluation. In this graph, nodes are model elements and edges are associations between elements. The evaluation of the constraint instance is equivalent to checking a particular property in the graph - such as the presence or the absence of a cycle. Solutions can then be generated on the graph, by adding or deleting edges and/or nodes. As there is a one-to-one mapping between the model elements and the graph nodes, and a one-to-one mapping between the model associations and the graph edges, it is straightforward to mirror the changes in the graph back to the model. If the model *is* a graph, which is the case with UML, then the solutions can be implemented directly on the model. The fixing of individual errors is described in Section 4.2.

Each error can have several solutions, and in many cases, more than one error will have to be fixed before the model satisfies all the instances of all the constraints. To fix the entire model, a tree is created to explore the combined effect of several fixes. The tree is rooted on the model to be fixed. Each node represents a version of the model, which can be correct or contain a number of errors. For each model that contains at least one error, one error is selected and solved. Each generated solution becomes a child of this node. A solution to fix the entire model is therefore a path from the root to a leaf that represents a correct model. The solution tree construction and properties are discussed in Section 4.3.

The number of generated solutions can be a problem, especially on large models with lots of errors. The more solutions are proposed, the harder it is for designers to

select the best solution. It is therefore crucial to order them in a meaningful way so the designer will first see the solutions he is most likely to select. The ordering is achieved by categorising solutions depending on the parts of the model they modify, and on the number of changes they require. The number of changes in a solution is not the same as the length of the path between the root and the solution, as fixes for individual errors can require *several* changes. This is taken into account when computing the "size" of each solution, as described in Section 4.4.

The easiest way of constructing the tree is to use a breadth-first or a depth-first approach. However, this is not the most efficient solution if one wants to get the smallest solutions as early as possible. In Section 4.5, improvements made to the tree construction algorithm are discussed, including:

- ordering the fixing of errors depending on the category of the constraints violated, an approach that is very similar to the ordering of OCL constraints discussed in Chapter 3;
- allowing users to eliminate some possible solutions that would modify elements or associations that they are not willing to modify;
- using heuristics to try to find the smallest solutions first.

In Section 4.6, the presentation of the solutions to the designer is examined.

## 4.2. Generating Fixes for Individual Constraints

### 4.2.1. Graph Representation of Constraints

DSML models can be seen as graphs whose nodes are elements and edges are associations between elements. Therefore, the validation of an OCL constraint against a particular

element can be treated as a graph problem. In `rbacDSML`, the OCL constraints can been classified in two categories: constraints whose evaluation succeeds when a particular cycle is found in the graph representation of the model, and constraints whose evaluation succeeds when a particular cycle is *not* found in the graph representation of the model. Changing the model to make it comply to a particular instance of an OCL constraint can then be reduced to creating or breaking cycles in a graph.

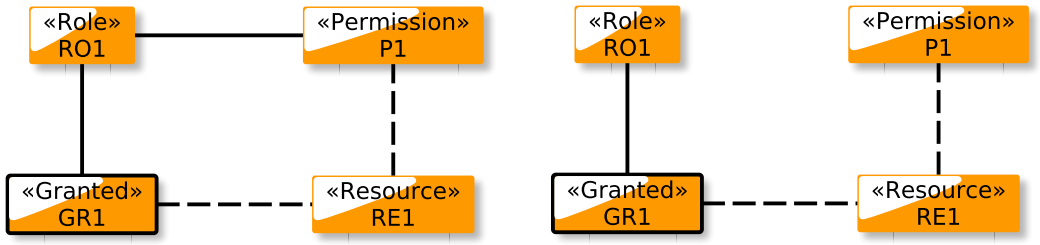
Of course, just because all `rbacDSML` OCL constraints happen to be classifiable in one of those two categories does not mean that *all possible* OCL constraints can be classified in one of those two categories. However, UML models *are* graphs, and therefore, all constraints can be seen as graph-related properties. More categories may need to be created for other DSMLs so each constraint can fit in at least one category.

### Type *I* - Finding Cycles in the Graph

Constraints in the first category look for a particular cycle in the graph. If the cycle exists then the constraint returns *true*, and if not, *false*. In fact, we look for some specific paths $A$ that start from the constraint's context, and for each one we expect that there exists at least one specific path $B$ from the end of $A$ back to the context, such that $A; B$ forms a cycle.

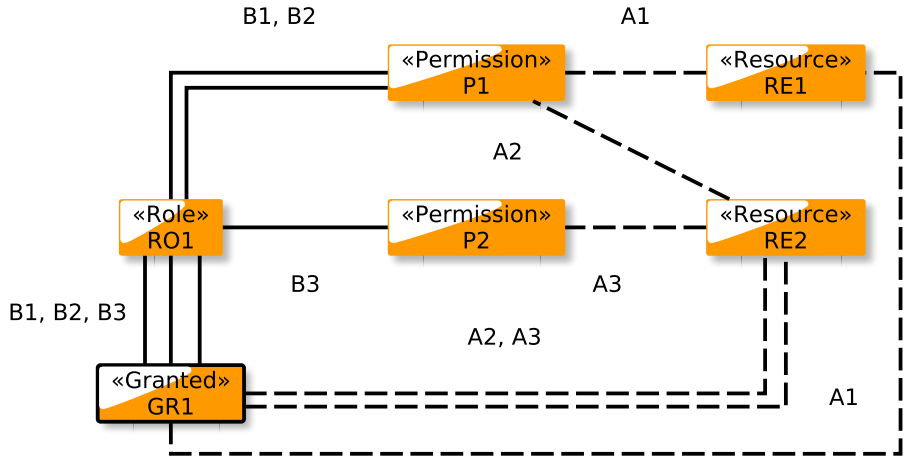
Two `rbacDSML` constraints fall into that category: the constraint that makes sure that activated roles have been assigned to the user (constraint 3.6), and the constraint that verifies that the model conforms to «`Granted`» scenarios (constraint 3.9). In general, constraints falling into this category can be defined as follows:

**Definition 4.** *A constraint from the "finding cycles" category is a constraint for which, if a particular path A is found from its context, then the path continues to form a particular kind of cycle - i.e. there is* another *path B from the end of the first path back to the*




**(a)** Correct - path $A$ dotted, path $B$ continuous

**(b)** Incorrect - path $A$ dotted, no path $B$, no cycle




**(c)** Correct - three cycles formed by $A$ and $B$ paths

**Figure 4.1.:** Examples for the Granted OCL constraint

*context. In other words,* $\forall A \exists B : A; B :\ start(A) = end(B),\ end(A) = start(B)$*, where* $start(A)$ *denotes the first node of path* $A$*, and* $end(B)$ *denotes the last node of path* $B$*.*

The first OCL constraint from `rbacDSML` to be expressed as a graph is constraint 3.9, that evaluates the model against «`Granted`» requirements. For the constraint to be satisfied, the set of permissions required by the resources used in the scenario ($S_{Perm\_required}$) must be a subset of the set of permissions activated for the scenario ($S_{Perm\_activated}$): $S_{Perm\_required} \subseteq S_{Perm\_activated}$. Translated to the graph representation, it means that the path $A$ is a path from the context (i.e. a granted node) to a permission node that passes through a resource node. The path $B$ completes the cycle by going back to the context through a role node.

The definition of the constraint can be expressed as the following specialisation of Definition 4:

**Definition 4.1.** *Given a «`Granted`» scenario node in the graph representation of the model, for* every *path A of length 2 from the scenario to a permission node and through a resource node, there must be a path B of length 2 from the permission node back to the scenario, through one role node. Together, these two paths form a cycle.*

Figure 4.1 illustrates the constraint for several simple examples. In that figure as well as in subsequent figures in this dissertation, the following notation applies: nodes represent UML model elements, except for associations that are represented by edges between associated nodes. The type of a node is given by the stereotype above its name. A dotted line represent an association that is part of an $A$ path, while a continuous line represents an association that is part of a $B$ path. Furthermore, a black border has been added to those nodes that represent a context element for the OCL constraint considered. One should also note that the graphs displayed in the figures are subsets of models, where all elements that are not relevant to the OCL constraint considered have been ignored. By definition, the context element is also the start of path $A$ and the end of path $B$.

Figure 4.1a is the smallest correct case: there is one path $A$ between the scenario and a permission, and there is another path $B$ from the permission back to the scenario, through a user.

Figure 4.1b is the simplest incorrect case: there is one path $A$ between the context and the permission, but no path from the permission back to the scenario. Therefore, the cycle is absent, and the constraint evaluates to *false*.

Figure 4.1c shows another correct model: there are *two* paths $A1$ and $A2$ between the scenario and different permissions, and each of these roles is the starting point of a path $B$, back to the scenario. There are then two cycles, and the constraint evaluates to *true*.

The second OCL constraint from `rbacDSML` in this category is constraint 3.6: to be satisfied, the set of roles activated by a scenario (either «`Granted`» or «`Forbidden`») must be a subset of the set of roles assigned to the user performing the scenario. Translated to the graph representation, it means that path $A$ is a path of length 1 from the context (a scenario) to a role. Path $B$ is a path of length $n|n \geq 2$, from the role back to the context and through a user. The length of the path can be greater than 2 if parent-child edges have to be followed between roles.

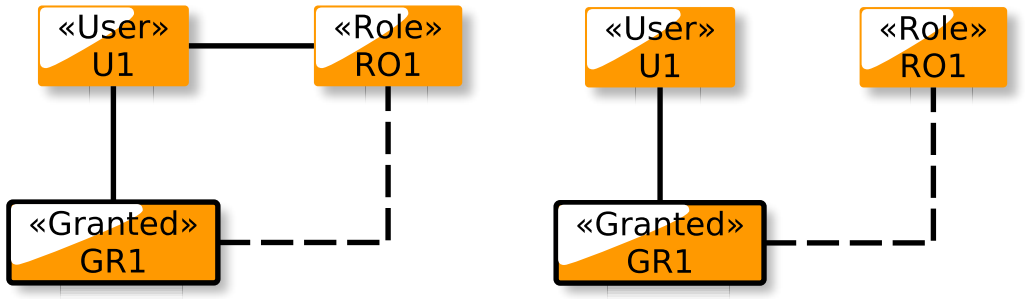
The definition of the constraint can be expressed as the following specialisation of Definition 4:

**Definition 4.2.** *Given a «`Granted`» or «`Forbidden`» scenario as the context in the graph representation of the model, for* every *path A of length one from the context to a role node, there must be a path B of length 2 or more from the role node to the context, through a user node, and possibly through several roles following parent-child edges. Together, these two paths form a cycle.*

Figure 4.2 illustrates the constraint for several simple examples. The first one (Figure 4.2a) shows the simplest correct case: the graph contains one path $A$ from a «`Granted`» scenario to a role, and one path $B$ from said role back to the scenario through a user. The constraint's evaluation returns *true*.

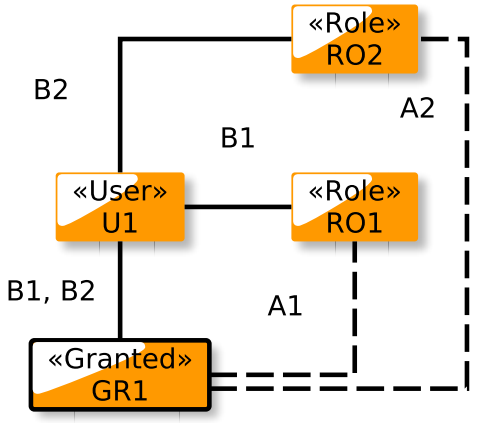
A counter-example is presented in the second example (Figure 4.2b). There is still one path $A$ between the scenario and the role, but this time there is no path $B$ from the role back to the scenario through a user. Therefore, the cycle is broken, and the OCL constraint's evaluation returns *false*.

The third example (Figure 4.2c) shows a more complex correct model. There are *two* paths $A$ (dotted) between a «`Granted`» scenario and two roles. Each path $A$ has a corresponding path $B$ (plain lines), from the role back to the scenario and through a user, completing both cycles. The constraint's evaluation returns *true*.




**(a)** Correct - there is a cycle

**(b)** Incorrect - path $A$ dotted, no path $B$




**(c)** Correct - paths $A$ dotted, paths $B$ continuous

**Figure 4.2.:** Graph representation of the `rbacDSML` constraint ActivateRoles

### Absence of Cycles

Constraints in the second category differ from constraints in the first category as they look for the *absence* of cycle, instead of their presence. This category can be divided in two sub-categories. The first one includes the constraints where, for *every* path $A$, there is no path $B$ to complete a cycle. The second one includes the constraints where *at least one* path $A$ has no path $B$ to complete its cycle.

**Type *II* - No Cycle at all** Constraints in the first sub-category succeed if, for every path $A$, there is no corresponding path $B$ to complete the cycle.

Two `rbacDSML` constraints fall into this sub-category: the SSoD (constraint 3.7) and DSoD (constraint 3.8) constraints, that ensure that models do not violate separation of duty constraints. In general, constraints falling into this sub-category can be defined as follows:

**Definition 5.** *A constraint from the "no cycles" category is a constraint for which, if a path $A$ is found from its context, then the path does* not *continue to form a specific cycle - i.e. there is* no *path $B$ from the end of the first path back to the context. In other words, $\forall A \nexists B : A; B :\ start(A) = end(B),\ end(A) = start(B)$, where $start(A)$ denotes the first node of path $A$, and $end(B)$ denotes the last node of path $B$.*

The first OCL constraint from `rbacDSML` in this sub-category is the SSoD constraint. Its context is a user. For the constraint to be satisfied, there cannot exist an SSoD relationship between two roles assigned to the user used as the context. Translated to the graph representation, it means that the path $A$ is a direct path from the context to a «`rbacRole`» node. The path $B$ completes the cycle by going back to the context through another «`rbacRole`» node using a SSoD edge, possibly following one or several child-parent edges before the SSoD edge.

The definition of the constraint can be expressed as a specialisation of Definition 5:

**Definition 5.1.** *Given a user node in the graph representation of the model, for* every *path A of length 1 from the user to a role node, there cannot be any path B of length* $n|n \geq 2$ *from the role node back to the user, through any number of child-parent edges, and through one SSoD edge. There cannot be a cycle formed by A and B.*

Figure 4.3 illustrates the constraint with simple examples. Figure 4.3a is the easiest correct case: there are two $A$ paths, but no $B$ path.

Figure 4.3b is correct too. There are the same two paths $A$ as in Figure 4.3a. Athough there is one SSoD edge, it is not part of a $B$ path back to the user.

Figure 4.3c is the simplest incorrect model. The path $A$, represented by the dotted line, has a corresponding path $B$ that completes the cycle. Therefore, the constraint evaluates to *false*.

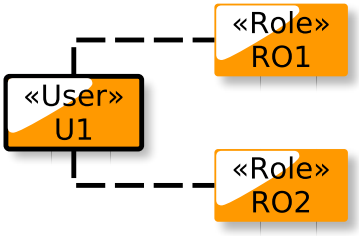
Figure 4.3d is another incorrect model. Here, there are not one, but *two* cycles, each formed of a path $A$ and a path $B$.

Figure 4.3e is an incorrect model involving a role hierarchy. Because $RO3$ is a descendant of $RO1$, it inherits its SSoD constraints. There is therefore a path $A$ from the context to $RO3$, and a path B from $RO3$ back to the context, through $RO1$ and $RO2$.

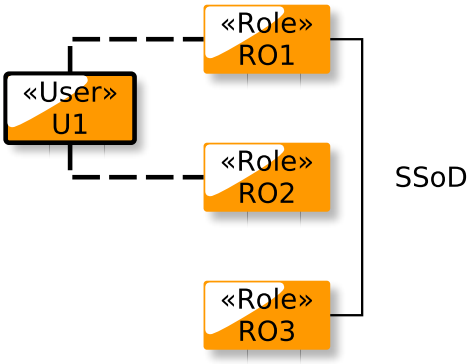
The second constraint from `rbacDSML` in this sub-category is the DSoD constraint. It is very similar to the SSoD constraint, except that the context is a scenario node (either «`Granted`» or «`Forbidden`»), and role hierarchies are ignored. For a discussion of separation of duty and role hierarchies, see Section 2.2.4 in the literature review.

The definition of the constraint is therefore very similar to Definiton 5.1, and is also a specialisation of Definition 5:

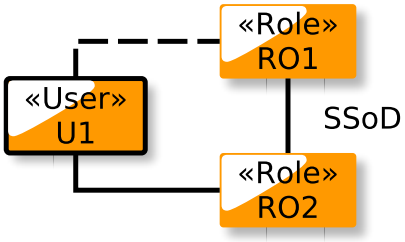
**Definition 5.2.** *Given a scenario (either «`Granted`» or «`Forbidden`») node in the graph representation of the model, for* every *path A of length 1 from the scenario to a*



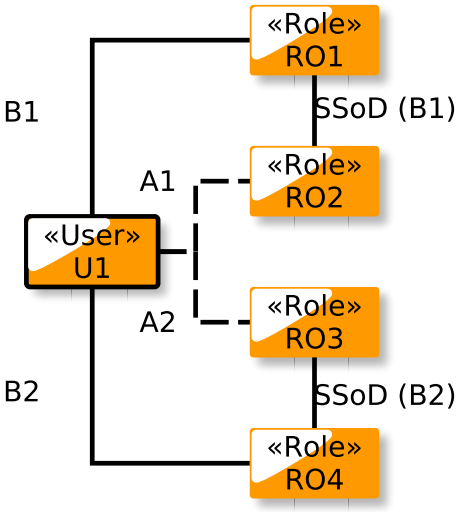

(a) Correct



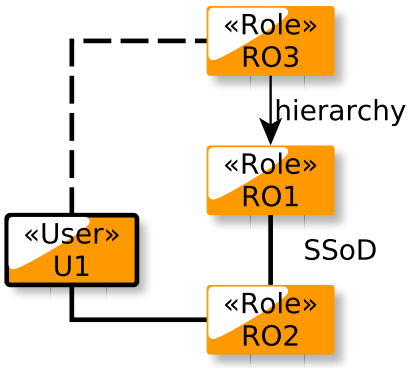

(b) Correct




(c) Incorrect

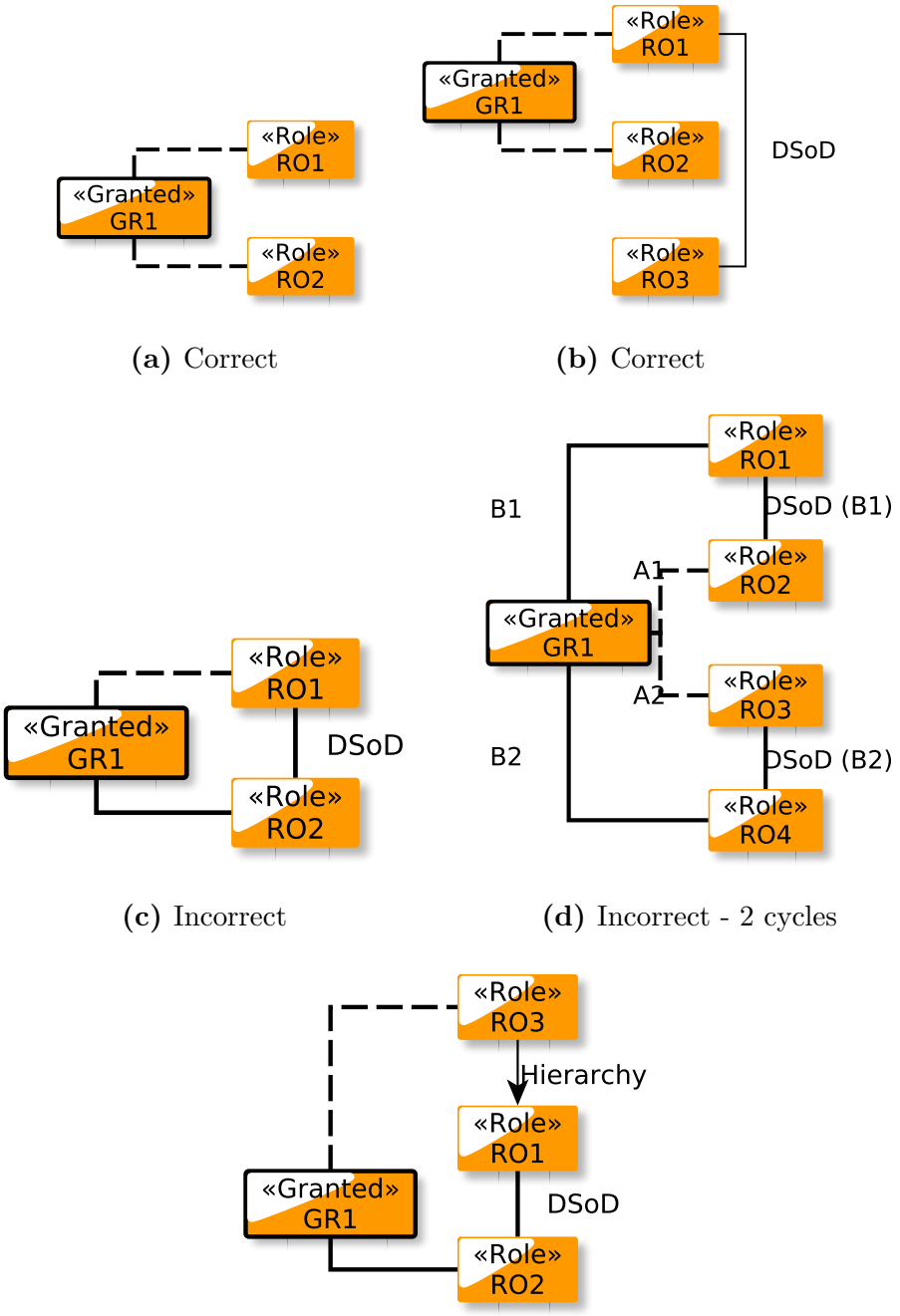



(d) Incorrect - 2 cycles




(e) Incorrect - role hierarchy

**Figure 4.3.:** SSoD graph examples




**(a)** Correct **(b)** Correct

**(c)** Incorrect **(d)** Incorrect - 2 cycles

**(e)** Correct - role hierarchy

**Figure 4.4.:** DSoD graph examples

*role node, there cannot be any path B of length 2 from the role node back to the scenario, through another role node by way of a DSoD edge. There cannot be a cycle formed by A and B.*

Figure 4.4 illustrates the constraint with simple cases. They are all very similar to Figure 4.3 illustrating the SSoD constraint, except that the context is a scenario instead of a user in Figure 4.3. The first two Figures (4.4a and 4.4b) are correct models, whilst the last two Figures (4.4c and 4.4d) are incorrect, because they do include cycles. The last one differs more from the SSoD version. The activation of $RO3$ does not mean that its parent $RO1$ is activated as well, and therefore the DSoD constraint between $RO1$ and $RO2$ is not part of a $B$ path. The constraint thus evaluates to *true*.

**Type *III* - At Least one Path Without a Cycle** Constraints in the second sub-category succeed if at least one path $A$ has no corresponding path $B$ to complete the cycle.

Only one `rbacDSML` constraint falls into this sub-category: the constraint that ensures that the «`Forbidden`» scenarios are enforced by the model (constraint 3.10). In general, constraints falling into this sub-category can be defined as follows:

**Definition 6.** *A constraint from the "at least one path without a cycle" category is a constraint for which, of all the paths $A$ starting from its context,* at least one of them *does* not *continue to form a specific cycle - i.e. there is at least one path $A$ that does not have a path $B$ back to the context. In other words, $\exists A : \nexists B : A; B : \ start(A) = end(B),\ end(A) = start(B)$, where $start(A)$ denotes the first node of path $A$, and $end(B)$ denotes the last node of path $B$.*

The only constraint of this type in `rbacDSML` is in constraint 3.10, that evaluates the model against «`Forbidden`» requirements. The constraint's satisfaction requirements are easily derived from the «`Granted`» constraint (listing 3.9). The set of permissions required by the resources used in the scenario must *not* be a subset of the set of permissions activated for the scenario, i.e. at least one of the required permissions must not be part of the permissions acquired through the activated roles. Translated to the graph

representation, it means that $A$ is a path from the context (i.e. a «`forbidden`» node) to a permission node that passes through a resource node. Path $B$ completes the cycle (except for at least one path $A$ where there cannot be a path $B$) by going back to the context through a role node.

The definition of the constraint can be expressed as the following specialisation of Definition 6:

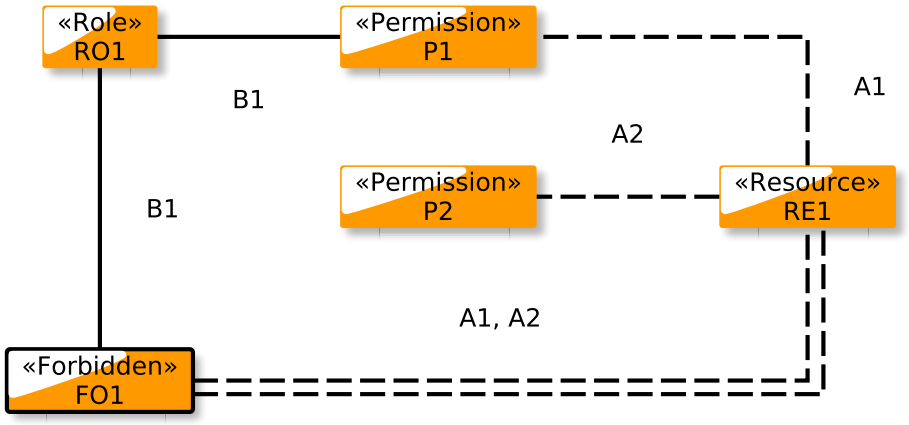
**Definition 6.1.** *Given a «`Forbidden`» scenario node in the graph representation of the model, there must be* at least one *path $A$ of length 2 from the scenario to a permission node and through a resource node, that does* not *have a corresponding path $B$ of length $n|n > 2$, from the permission back through the context, through one role, and possibly more roles along child-parent edges.*

Figure 4.5 illustrates the constraint with a simple example. Figure 4.5a has two paths $A$, $A1$ and $A2$, but only $A1$ has a corresponding $B$ path. Therefore, the constraint evaluates to true.

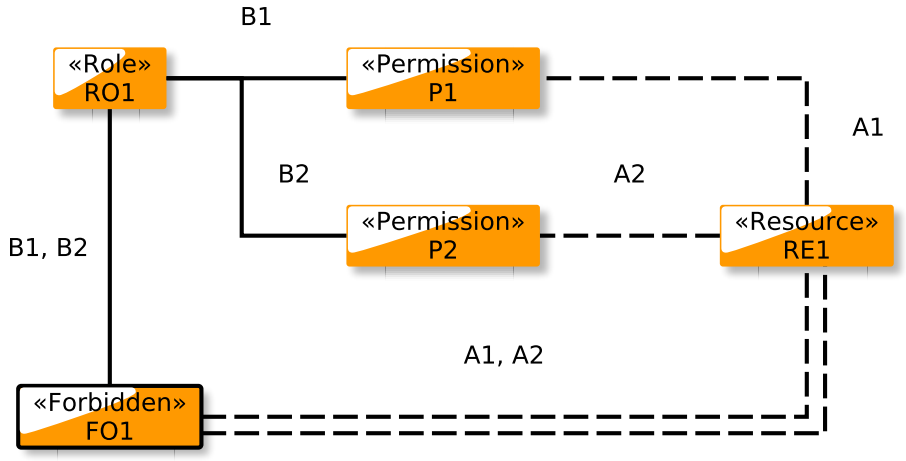
Figure 4.5b, however, has a $B$ path for each of the $A$ paths, and hence the constraint evaluates to false.

### 4.2.2. Generating Possible Fixes

The previous section discussed how to express OCL constraints as graph problems where specific cycles must be either found or not for the constraint to evaluate to *true*. Therefore, a constraint that evaluates to *false* will either have a cycle where there shouldn't be one, or no cycle where there should be one. Fixing a model for it to satisfy a particular constraint then becomes a matter of either completing or breaking cycles. This section explores how this can be done, and shows how to generate all the possible fixes for a particular instance of a constraint only by examining the OCL constraint and the




**(a)** Correct - path $A2$ has no corresponding path $B2$




**(b)** Incorrect - no path $A$ without a corresponding path $B$

**Figure 4.5.:** «`Forbidden`» graph example

profile meta-model. Whilst this section focuses on fixing the model so they conform to a particular instance of a particular OCL constraint, the next section will combine these fixes to generate a series of changes that make *entire* models correct.

### Anatomy of a Fix

A fix is, as it has been indicated earlier in this chapter, a change to a model that will make the model satisfy a particular instance of a particular OCL constraint. There are two ways of changing a model: either *adding* elements, or *removing* elements. One could argue that there is a third way of changing a model, namely modifying an element, but this can be emulated by removals and additions. In particular, removing a class is removing it *and* all its associations.

In a single fix, *several* elements can be added or removed from the model. This section will provide numerous examples of fixes that involve more than one change. Change and fix can then be defined as the following:

**Definition 7.** *A* change *is a single unit of modification in a model. It can either be the* addition *of a new node or edge, or the* removal *of an existing one.*

When considering a list of several changes to the same model, one needs to make sure that the changes are *coherent*, e.g. that the same edge is not deleted twice. A coherent list of changes is defined as follows:

**Definition 8.** *A list of changes* $C_0, \ldots, C_n$ *is* coherent*, if and only if, for each change* $C_i, 0 \leq i < n$ *in the list,* $C_i$ *can be applied to the model resulting from the consecutive and ordered application on the initial model of all* $C_j, 0 \leq j \leq i-1$*.*

We can then define a fix as the following:

**Definition 9.** *A* fix *for an instance of an OCL constraint on a model is an ordered, non-empty list of* coherent changes *made to the model that leads the model to a state*


**(a)** Left hand side: an erroneous model, according to an imaginary OCL constraint

**(b)** Right hand side: the model, fixed by the addition of a new node, and then the addition of a new edge

**Figure 4.6.:** A simple example that illustrates why a fix needs to contain an *ordered* list of changes

*where the instance of the OCL constraint evaluates to* true*. A fix only exists for a particular model if said model, before the fix, causes the instance of the OCL constraint to evaluate to* false*.*

The above definition specifies that a fix needs to be an *ordered* list of changes. Consider the following example, illustrated on Figure 4.6. The model on the left hand side (4.6a) is the original, and the model on the right hand side (4.6b) is the result of an imaginary fix for an instance of an imaginary OCL constraint. The fix consists of two changes: first, adding a new node, and second, adding a new edge between the new and the existing nodes. It is clear that adding the new node must be done before adding the edge, otherwise the latter would have a dangling end.

Fixes can be as small as one change, or they can contain a very long list of changes. Furthermore, depending on the DSML, not all changes are necessarily equal. For example, in `rbacDSML`, adding a new role to a model could be treated as a more "expensive" change than adding a user - role assignment, since presumably, creating a new role in an organisation is a more serious and less frequent operation than giving someone one existing role. Therefore, it is interesting to provide a way of computing the *weight*, or *cost*, of a fix. This function is called $fcost(F)$, for any fix $F$. The definition of the function depends on the DSML, and possibly depends on the designer too. A change can have a cost function too, $ccost(C)$ for any change $C$, that can be used to compute the cost of a fix. The simplest cost function would be $fcost(F) = 1$, and all fixes, no matter how

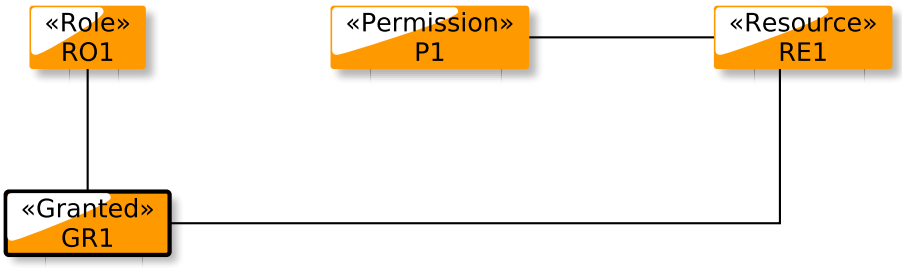



**Figure 4.7.:** There are an infinite number of ways to fix this model

many changes or what kind of changes they contain, would have the same cost. Another option would be to use the sum of each change in a fix: $fcost = \sum_{i=1}^{s} ccost(C_i)$, where $s$ is the number of changes in the fix.

### Completeness and Correctness

It is essential for the generation of fixes to satisfy two properties, correctness and completeness.

**Definition 10.** ***Correctness****: every fix generated* must *lead to a model that satisfies the instance of the OCL constraint considered.*

**Definition 11.** ***Completeness****: the fixes generation algorithm must generate* all *the possible changes that would satisfy the correctness criterion.*

Verifying correctness is relatively easy: after the model has been changed according to the proposed fix, the instance of the OCL constraint considered must evaluate to *true*, i.e. the model must then satisfy the graph-based definition of the constraint. Verifying completeness is a bit more challenging. In fact, it is necessary to somewhat restrict the notion of completeness in order to only generate a finite amount of possible fixes, when adding elements to the model [1]. The problem can be illustrated with an example such as the example on Figure 4.7. It depicts a rather simple model. The reader will easily

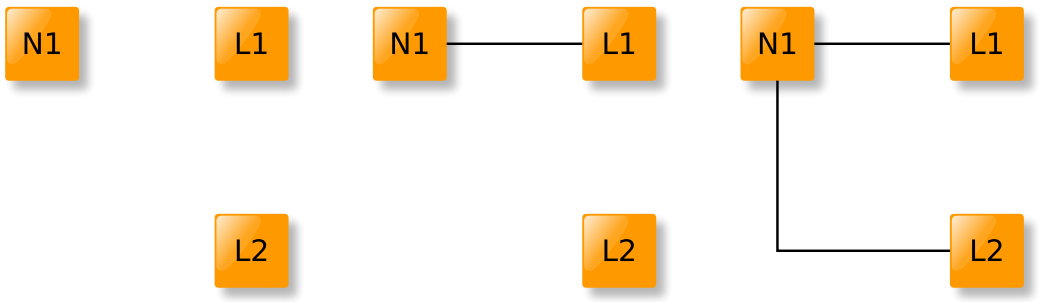
[1]The deletion of elements from the model (without any addition) is necessarily finite: at most, all the elements will be deleted.

spot the error with the «`Granted`» constraint: `P1` is required by `RE1`, but not given to `RO1`. There are an infinite number of ways to fix this constraint: first, one could assign `P1` to `RO1`. Alternatively, one could create a *new* role, `RO2`, activate it from `GR1`, and assign `P1` to it. That new role could have any name that has not already been given to another element: `RO2`, `RO42`, `Arthur`, `teapot`, etc. However, depending on the profile considered, the name may or may not be important. With `rbacDSML` for example, the name of an automatically created role, or the name of an automatically created element, does not matter the slightest. If a meaningful name has to be chosen, then it cannot be done automatically, and the designer will have to choose it himself. The consequence is that one can define, for `rbacDSML`, an equivalence class that encompasses all the possible *new* elements generated by a fix to a model, that only differ by their name. When creating new nodes or edges for the purpose of a fix, the name of the new element does not matter, and two elements of the same type and with edges to the same nodes are indistinguishable.

Another way in which an infinite number of changes could potentially be generated is if fixes that are not minimal are generated. A minimal fix is defined as follows:

**Definition 12.** *A fix is* minimal *if there does not exist any strict subset of its changes that would also make a valid fix.*

Figure 4.8 illustrates the minimal fix property on an imaginary model. The constraint to fix in this case says that every node $N_x$ should have at least one edge to a node $L_y$. The first model is the incorrect model. The second model is the minimal fix: only *one* edge has been added, and the constraint is now satisfied. The third model shows a fix that is not minimal: *two* edges have been added. The reader will immediately notice that the first fix is a subset of the second one. If such non-minimal fixes are allowed, an infinite number of fixes could be generated.




**(a)** Incorrect model **(b)** Minimal fix **(c)** Non-minimal fix

**Figure 4.8.:** Minimal and non-minimal fixes

These two properties guarantee that the number of possible fixes for any error is a finite number. We already know that fixes that only differ by the name of the new nodes will be counted as only one fix, and Definition 12 guarantees that only minimal fixes will be generated, therefore forbidding the generation of an infinite number of non-minimal fixes.

### Breaking Cycles - Fixing Type *II* Constraints

Breaking cycles is the easiest type of fix that can be applied. Constraints that fall into the category where no cycles of a certain type can be found are all expressed as follows: "*If there exists a path* A*, then there cannot exist another path* B *that completes a cycle*". If a cycle is found, there are therefore two solutions: either break $A$, or break $B$. These two solutions can be merged into one: *break the cycle formed by* A*;* B.

Of course, breaking a cycle only involves removing a single edge, which represents an association. Completeness is guaranteed: since there is a finite number of associations in a model, there is also a finite number of combinations of associations (one for each cycle to break) to remove.

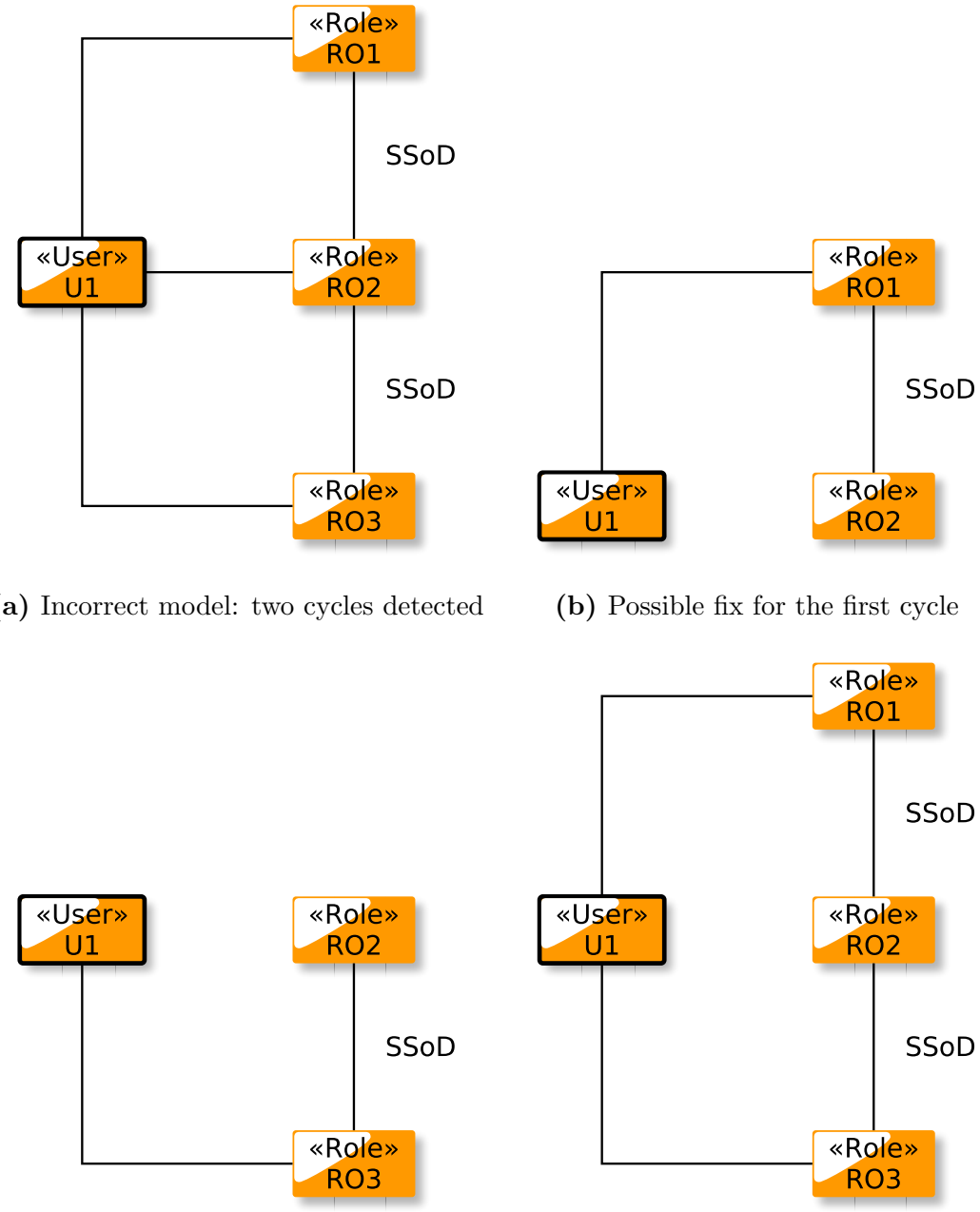
Since only *edges* are removed, the order of the changes in a fix do not matter. And because of the minimal fixes requirement, the number of fixes to generate to break a cycle is $n$, a much more manageable number of possibilities. There are $n$ fixes made of exactly one change, and all other fixes are supersets, and therefore should be discarded. A generic algorithm that generates minimal fixes for breaking paths[2] is Algorithm 1.

**Algorithm 1** Generating fixes by breaking a path

```
function BreakPath(path)
    fixes ← ∅
    for all edge in path do
        fix ← new Fix()
        change ← new DeleteChange(edge)
        Append(fix, change)
        Append(fixes, fix)
    end for
    return fixes
end function
```

Sometimes, *several* cycles need to be broken in order to create a fix. Fixes can be generated for breaking each cycle individually then merged together. A merged fix will be the concatenation of a fix for each cycle to be broken. Because there can only be edge removals, there is no need to worry about potential conflicts or order. However, duplicates are possible, as illustrated in Figure 4.9. In that case, only one of the duplicate changes is kept in the merged fix. The figure shows the case where both cycles are broken by deleting the same edge. Figure 4.9a is the incorrect model, which has two cycles. Figure 4.9b shows a possible fix for the first cycle, whilst Figure 4.9c shows a possible fix for the second cycle. Instead of merging both fixes into one fix with the same edge to be deleted twice, there will only be one change in the fix, and the edge will only be deleted once. The result is shown on Figure 4.9d. Algorithm 2 can be used to merge two fixes. Algorithm 3 minimises a list of fixes, i.e. removes from the list the fixes that are supersets of another fix in the list. More fixes can be merged by applying the merging algorithm

[2]Note that a cycle *is* a path whose origin and target are the same node.




**(a)** Incorrect model: two cycles detected

**(b)** Possible fix for the first cycle

**(c)** Possible fix for the second cycle

**(d)** One fix breaks both cycles

**Figure 4.9.:** Duplicates when breaking several cycles

several times. Two lists of fixes can be merged with Algorithm 4, while Algorithm 5 will generate all the fixes for an error, no matter how many cycles there are.

**Algorithm 2** Merging two *breaking cycle* fixes

```
function MERGE(fix_a, fix_b)
    fix_m ← fix_a
    for all change in fix_b do
        if ¬ CONTAINS(fix_a, change) then
            APPEND(fix_m, change)
        end if
    end for
    return fix_m
end function
```

**Algorithm 3** Removing non-minimal fixes from a list

```
function MINIMISE(fixes)
    for all fix_a in fixes do
        for all fix_b in fixes do
            if CONTAINS(fix_a, fix_b) then
                REMOVE(fixes, fix_a)
            end if
        end for
    end for
    return fixes
end function
```

**Algorithm 4** Combining the fixes from two lists

```
function COMBINE(fixes_a, fixes_b)
    fixes ← ∅
    for all fix_a in fixes_a do
        for all fix_b in fixes_b do
            fix ← MERGE(fix_a, fix_b)
            if ¬ CONTAINS(fixes, fix) then
                APPEND(fixes, fix)
            end if
        end for
    end for
    fixes ← MINIMISE(fixes)
    return fixes
end function
```

**Algorithm 5** Generating fixes by breaking all cycles

```
function GenerateFixesBreakAll(root)
    fixes ← ∅
    cycles ← FindCycles(root)
    for all cycle in cycles do
        fixes_tmp ← BreakPath(cycle)
        fixes ← Combine(fixes, fixes_tmp)
    end for
    return fixes
end function
```

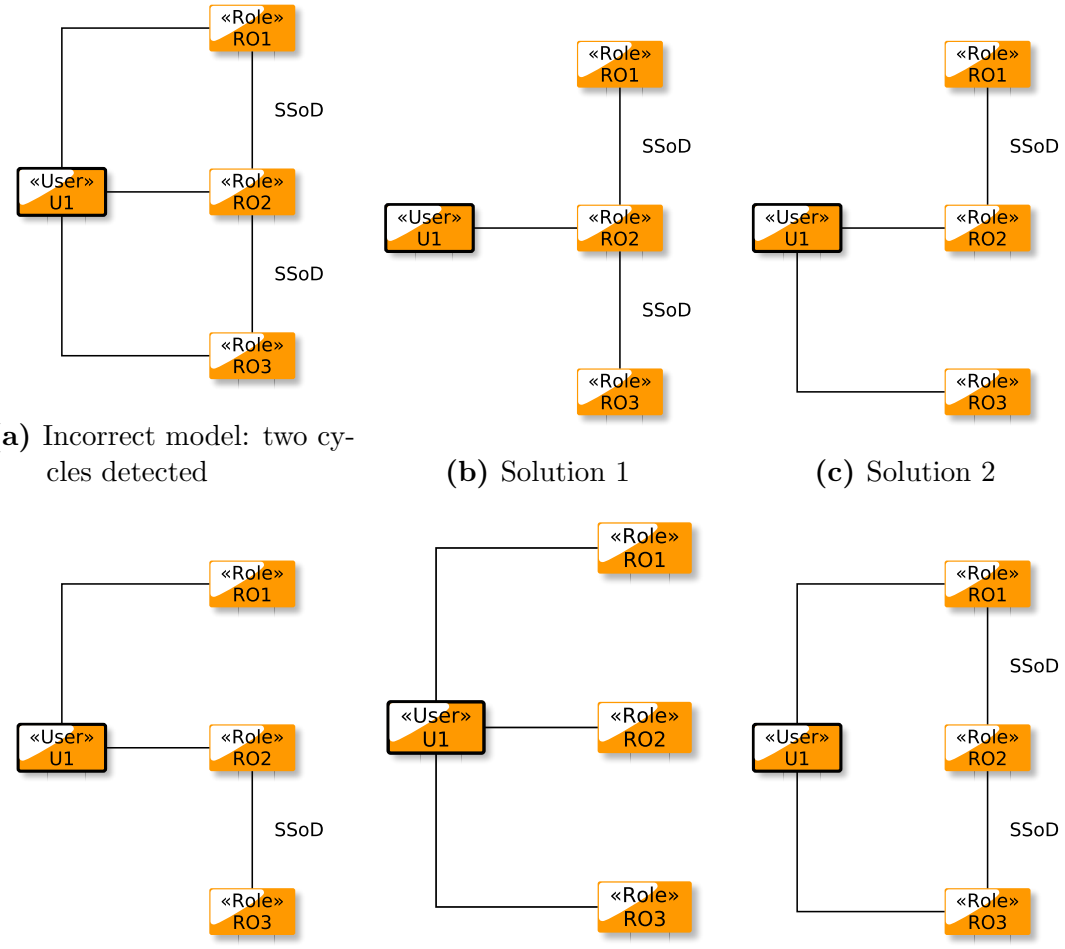
The case of `rbacDSML` is quite simple when it comes to breaking cycles. The two OCL constraints whose fix generation strategy involves breaking cycles are those that ensure that the model conforms to the SSoD and DSoD constraints. As both constraints have similar graph representations, they also have similar cycle breaking strategies.

The SSoD constraint is illustrated in Figure 4.10. The first model is the original model showing a violation of the SSoD constraint represented by the two cycles. The other models are the five possible *minimal* fixes that solve the problem and make the model conform to the SSoD constraint. Other fixes are possible when combining the fixes to break each individual cycle, but they all involve deleting the edge between $U1$ and $RO2$ as well as deleting another edge. Since deleting the edge between $U1$ and $RO2$ is, alone, a solution to break both cycles, these other fixes are not minimal, and therefore should be discarded.

The DSoD constraint is very similar (the context is a «`Granted`» element instead of a «`User`» element), and illustrated in Figure 4.11.

### Breaking Cycles - Fixing Type *III* Constraints

The case of the «`Forbidden`» constraint is a bit different. It is of the type "*There is at least one path A for which there is no path B so the combination of A and B forms a cycle*", i.e. the constraint is violated if $\forall A \exists B$. Two types of fixes are possible here. One




**(a)** Incorrect model: two cycles detected

**(b)** Solution 1

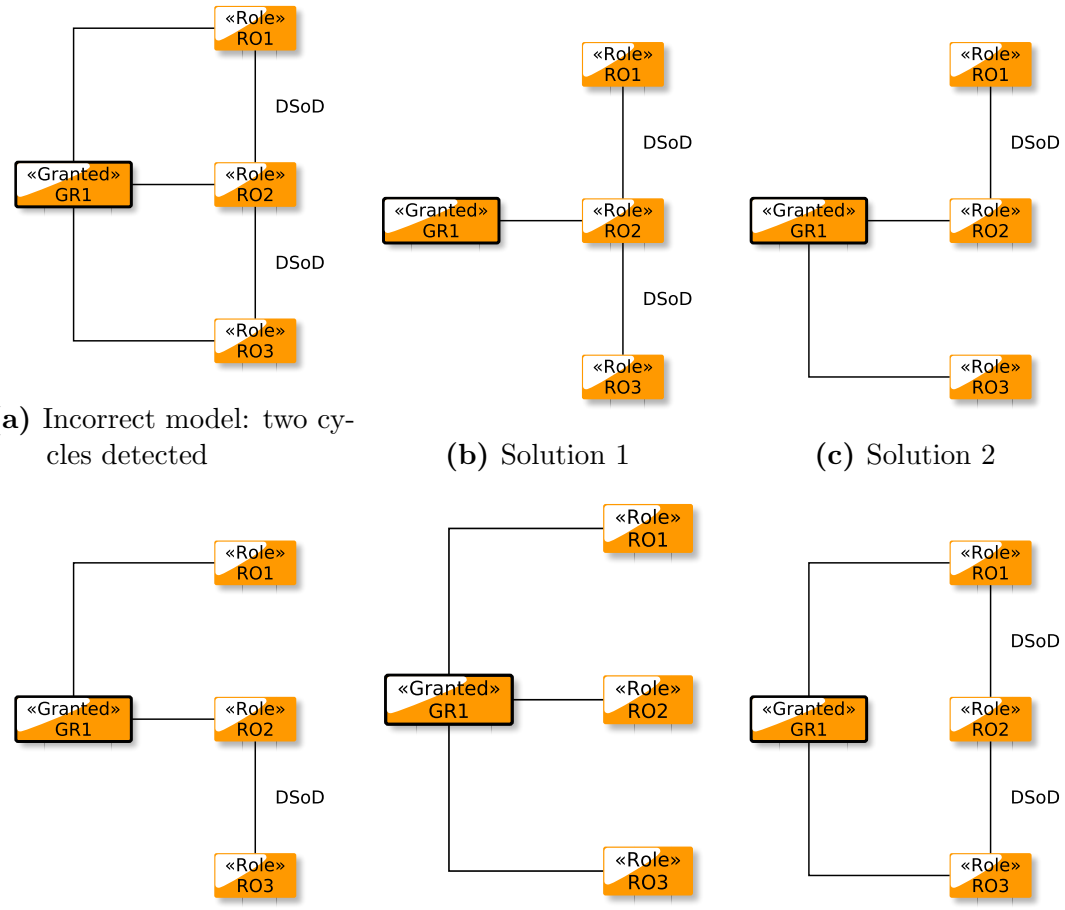
**(c)** Solution 2

**(d)** Solution 3

**(e)** Solution 4

**(f)** Solution 5

**Figure 4.10.:** All the minimal ways of fixing an SSoD error




**(a)** Incorrect model: two cycles detected

**(b)** Solution 1

**(c)** Solution 2

**(d)** Solution 3

**(e)** Solution 4

**(f)** Solution 5

**Figure 4.11.:** All the possible ways of fixing a DSoD error

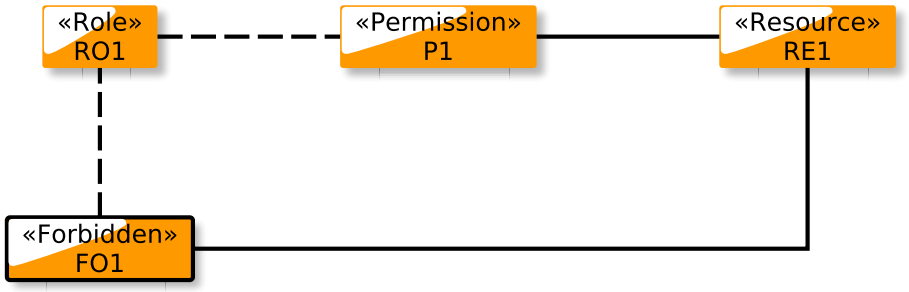



**Figure 4.12.:** Breaking a path $B$ to fix an error in a «`forbidden`» constraint. Either of the two dotted edges can be removed to break the path

of the paths $B$ could be broken, which would leave an "orphaned" path $A$. Alternatively, a new path $A$ could be created so that there is no corresponding path $B$. It is worth examining each option separately.

The first option is to break one $B$ path (breaking more than one $B$ path would violate the minimal fix requirement). This is fairly easy and can be done in a way that is very similar to Algorithm 5. Note that breaking $A$ would not be an acceptable solution: that path would simply "disappear" from the constraint evaluation, leaving only cycles. Algorithm 6 shows how the fixes can be generated. The `GetPathB` function depends, of course, on the constraint being considered.

**Algorithm 6** Generating fixes; each fix breaks only one cycle

```
function GenerateFixesBreakOne(context)
    fixes ← ∅
    cycles ← FindCycles(context)
    for all cycle in cycles do
        path ← GetPathB(cycle)
        fix ← Break(path)
        Append(fixes, fix)
    end for
    return fixes
end function
```

Figure 4.12 shows an example of how to fix an error in a «`Forbidden`» constraint by breaking one of the paths $B$.

The second option is to create a new path $A$ that has no path $B$ to complete its cycle. There are two kinds of fixes to add a path $A$: the fixes that only create new edges, and the fixes that also create new nodes.

In the first case, the goal is to create a path $A$ between the context and a target node that is not already reachable by a path $A$, while making sure that there is no path $B$ from that node, by deleting said paths $B$ if necessary. The solution therefore comes down to adding all the possible combinations of edges that will create such a path. Each fix should only create one path to avoid violating the minimal changes requirement. Figure 4.13 is an example of such an operation, on a model that violates a «`Forbidden`» constraint. Paths $A$ can be created between the context and one of the following nodes: $P3$ or $P4$. For example, to add a path to $P3$ (as show in the Figure), the following fixes are possible:

- add edge between $RE1$ and $P3$;
- add edge between $RE2$ and $P3$;
- add edge between $FO1$ and $RE3$, and add edge between $RE3$ and $P3$;
- add edge between $FO1$ and $RE4$, and add edge between $RE4$ and $P3$.

Of course, on the same example, a path $A$ could be created between the context and $P4$, in a similar way. It is not shown on the Figure in order to keep it readable.

Once this is done, there are two possibilities: either there is no path $B$ from $P3$ back to the root, and the fix is valid. Or there is a path $B$, and it should be broken, and the two fixes should be merged, using the algorithms described in the previous section.

In the second case, the goal is to create a *new* node, and then to create a path from the root to it. This works in the same way as the previous case, except that one does not need to worry about an hypothetical $B$ path: the node is new so there cannot be any.

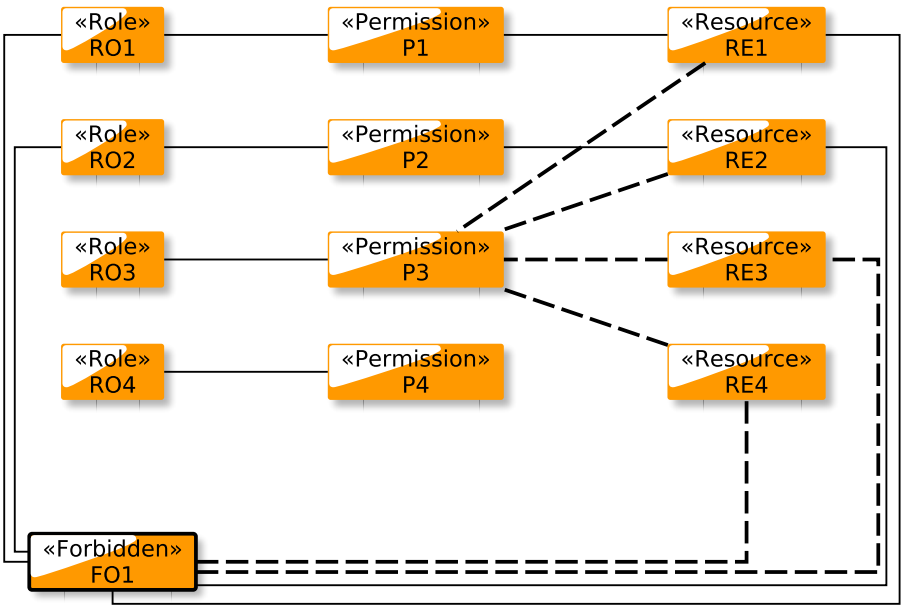



**Figure 4.13.:** Fixing error by creating new paths $A$ to $P3$ (dotted lines are possible additions)

Figure 4.14 is an example of such an operation. Here, permission $P5$ is added, and all the possible paths are generated as separate fixes. The following fixes are therefore possible:

- add $P5$, and add edge between $RE1$ and $P5$;
- add $P5$, and add edge between $RE2$ and $P5$;
- add $P5$, add edge between $FO1$ and $RE3$, and add edge between $RE3$ and $P5$;
- add $P5$, add edge between $FO1$ and $RE4$, and add edge between $RE4$ and $P5$;
- add $P5$, add $RE5$, add edge between $FO1$ and $RE5$, and add edge between $RE5$ and $P5$.

Interestingly, in this sub-category of constraints, there is always only one cycle to break *or* one path $A$ to create: any more would violate the minimal changes rule. Therefore, it is not necessary to merge different fixes.

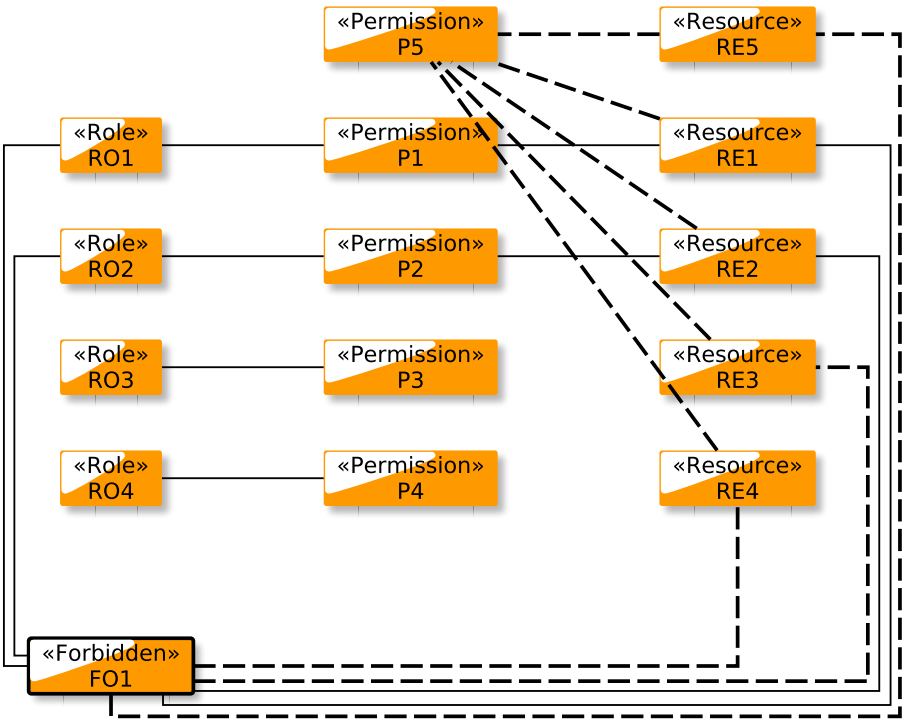



**Figure 4.14.:** Fixing error by creating new nodes (dotted lines are possible additions)

### Creating Cycles - Fixing Type *I* Constraints

The last type of fix to be applied is completing cycles. Constraints that fall into the category where cycles have to be found are all expressed as follows: "*If there exists a path A, then there must exist a path B that completes a cycle*". Therefore, a violation appears if and only if there is a path $A$ without a path $B$. This is very similar to the fixing generation for constraints such as the «`Forbidden`» verification constraint, except that the solution is the other way around: either a path $A$ is deleted, or a path $B$ is created.

Creating a path $B$ can be done using the exact same algorithm as the one used to create a path $A$ in the previous section. Conversely, deleting a path $A$ can be done using the exact same algorithm as the one used to delete a path $B$ in the previous section.

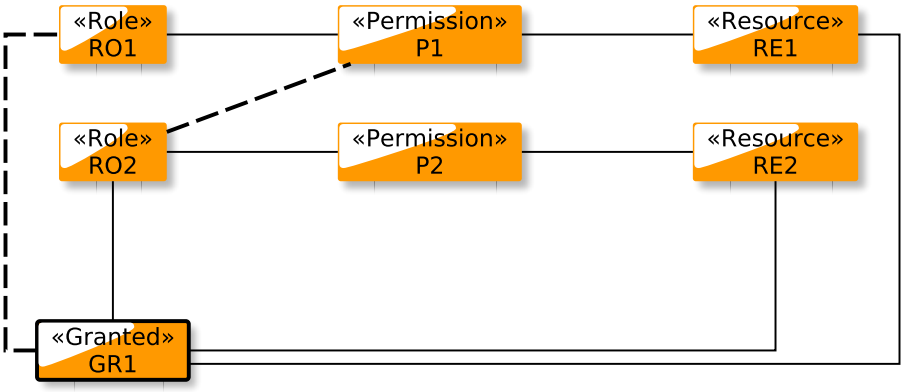



**Figure 4.15.:** Fixing error for «`Granted`» (possible additions dotted)

In `rbacDSML`, two constraints can be fixed by creating cycles. The first one is the «`Granted`» scenario verification constraint, for which an example is provided in Figure 4.15. The following operations can be performed to fix the broken cycle problem:

- add edge between $P1$ and $RO2$ (shown on figure);
- add edge between $RO1$ and $GR1$ (shown on figure);
- add $RO3$, add edge between $P1$ and $RO3$, and add edge between $RO3$ and $GR1$;
- delete edge between $RE1$ and $P1$;
- delete edge between $GR1$ and $RE1$.

The other constraint is the one that makes sure that roles activated by a scenario have been assigned to the user. This constraint requires a subtle change to the algorithm. The meta-model extension of UML for `rbacDSML` defines that there must be *exactly one* association from a scenario (either «`Forbidden`» or «`Granted`») to a user. This association could also be represented by an edge on a potential path $B$. Therefore, the algorithm that generates path $B$ must be adapted to avoid the creation of a second user, as it would violate the meta-model. The replacement of a user with another one is made of two changes: the deletion of the old edge and the addition of the new one. It will be

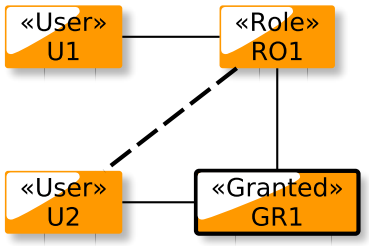



**Figure 4.16.:** Creating path $B$ with a meta-model multiplicity constraint (possible addition dotted)

referred to as a *replacement* for clarity. Figure 4.16 shows a sample model that violates the constraint. There is a path $A$ from the context to $RO1$ but not path $B$ from $RO1$ back to the context. The possible solutions are the following:

- add edge between $U2$ and $RO1$ (shown on figure as a dotted line);
- remove edge between $GR1$ and $RO1$;
- remove edge between $U2$ and $GR1$, and create edge between $U1$ and $GR1$.
- create node $U3$, replace edge between $U2$ and $GR1$ with edge between $U3$ and $GR1$, and add edge between $U3$ and $RO1$.

The last two possibilities illustrate the change in the algorithm: every addition of an edge between a user and a scenario must come with the removal of the existing edge between another user and the scenario, since the scenario can only be associated to one user.

## 4.3. Fixing an Entire Model

Fixing an entire model is a complex task: an incorrect model may violate OCL constraints in many places, and each and every fix to a particular instance of a constraint can in turn cause other constraint errors that did not exist before. In this section, a general

solution is discussed and analysed. The next section then focuses on how to improve the algorithm to make it faster.

Any algorithm to generate fixes for an entire model must satisfy several properties, some of which are similar to the properties that a solution for generating fixes for individual errors must satisfy:

- **Correctness**: All the generated fixes must lead to a model that does not violate any instance of any OCL constraint;
- **Completeness**: All the possible fixes must be generated, for the designer to be able to choose the most appropriate one;
- **Termination**: The generation process must always terminate: it cannot run forever.

### 4.3.1. Building a Solution Tree

To fix an entire model is to progressively fix individual errors of instances of OCL constraints, until a model that does not violate any instance of any constraint is produced. Since there might be several ways to fix each individual error, many different branches must be explored. In fact, a tree structure is a very way practical to represent the search for a solution. Figure 4.17 is a very abstract view of the solution. The model to be fixed is the root of the tree. Each node of the tree is a model, and each edge represents a fix of a single instance of an OCL constraint. Each node has a state, which is either *correct* if the model satisfies all the constraints, in which case that node is a leaf, or *incorrect* if there is at least one violation of a constraint. Therefore, each path from the root to a leaf represents the successive fixes that lead to a correct model.

A naive implementation would therefore use either a depth-first search (DFS) or a breadth-first search (BFS) approach to progressively construct the tree of possible

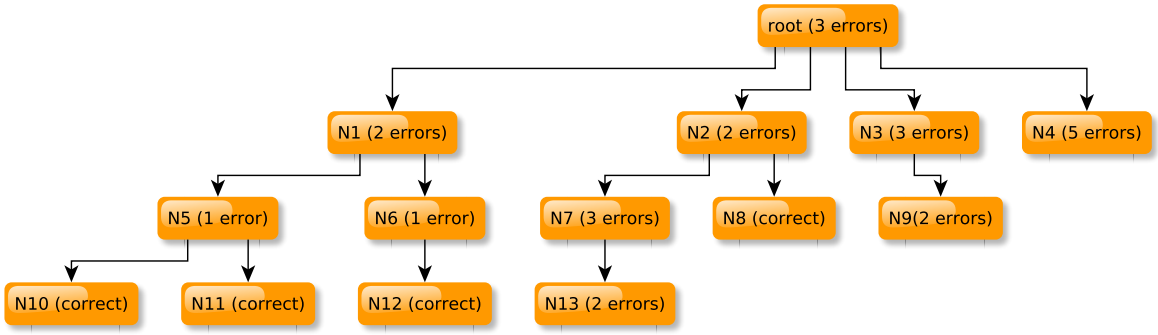



**Figure 4.17.:** Abstract view of the solution tree construction approach

solutions. Algorithm 7 sketches the BFS version of the algorithm. In the algorithm, the `GetModel` function creates a model from a node, by successively applying fixes to the model from the root node down to the node being considered. The `GenerateNodes` turns a list of fixes into new nodes that are children of the node passed as the first argument. The implementation of these two functions depends on the implementation of nodes, and is not provided here. The `GenerateFixes` function is not shown in this dissertation either, as its implementation is trivial but depends on the particular constraints in the profile, and their categorisation. The function simply detects the constraint that caused the error, then infers the category it belongs to. It then calls the appropriate function for the category, e.g. `GenerateFixesBreakAll` (Algorithm 5).

The DFS version of Algorithm 7 can of course be obtained by replacing the queue with a stack in the BFS algorithm.

In Algorithm 7, the `PickError(Model model)` function chooses one of the instances of OCL constraints that are violated by the model.

The algorithm is simple: starting from the initial model as the root, it progressively generates all the fixes for a particular instance of an OCL constraint. It stops when all solutions have been found.

**Algorithm 7** Naive BFS implementation of the model fixing algorithm

```
function FixModel(root)
    queue ← ∅
    Enqueue(queue, root)
    while ¬ IsEmpty(queue) do
        node ← Dequeue(queue)
        model ← GetModel(node)
        if ¬ Correct(model) then
            error ← PickError(model)
            fixes ← GenerateFixes(error)
            childrenNodes ← GenerateNodes(node, fixes)
            EnqueueAll(queue, childrenNodes)
        else
            //A solution has been found
        end if
    end while
end function
```

Let us examine how the algorithm behaves with regard to the three essential properties expressed earlier in this section. The algorithm is correct: each step involves the verification of the entire model, it only stops when correct solutions are found. The algorithm is complete: for each error of an instance of an OCL constraint, it explores *all* the possible fixes, recursively. The algorithm has *no* guarantee to terminate. The following scenario is possible, as illustrated in Figure 4.18: at some point in the resolution tree, there is an incorrect model, and an error $e_1$ is selected to be resolved. All the children of that model are therefore models that do not include $e_1$, since the corresponding instance of OCL constraint now evaluates to *true*. One of these children has one error, $e_2$, that was *not* part of the parent model. The generation of all the solutions to fix $e_2$ includes a model that raises $e_1$ again. The algorithm will not prevent this scenario to continue indefinitely, and the algorithm will never terminate.

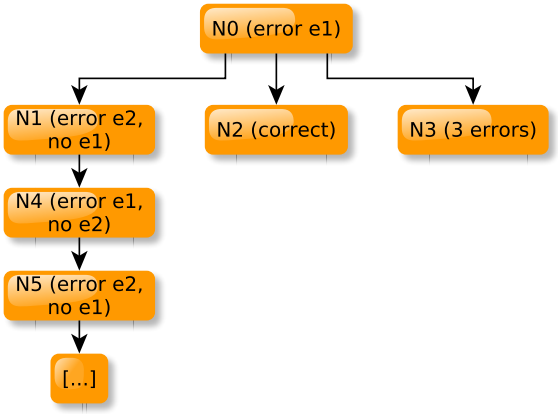



**Figure 4.18.:** An endless series of changes

### 4.3.2. Termination Guarantee

To solve this problem, a maximum depth $MAX\_D$, defined by the designer, is introduced. It provides a limit on the depth of the tree. Since the tree has a maximum depth of $MAX\_D$ and each node has a finite number of children, the algorithm will necessarily terminate. This, however, affects the completeness criterion: solutions comprising more than $MAX\_D$ fixes will not be explored. Completeness then has to be redefined as the following:

**Definition 13.** ***Completeness*** *(revisited): the fixes generation algorithm must generate* all *the possible solutions up to a maximum tree size of $MAX\_D$, where $MAX\_D$ is a designer-defined constant.*

This depth-restricted definition of completeness has a practical benefit: Defining $MAX\_D$ enables designers to manage execution time. Since large and complex models can produce enormous solution trees and computational resources are usually limited, keeping execution time within limits can be crucial. It may therefore be practical for designers to start the execution with a low $MAX\_D$ and gradually increase the constant in repeated executions until a satisfactory solution is found.

Algorithm 8 is the adapted version of Algorithm 7 with the restriction on the size of the tree. It still satisfies the correctness criterion, it is complete according to the limited definition above, and it is guaranteed to terminate.

**Algorithm 8** Size-limited, BFS implementation of the model fixing algorithm

```
function FixModel(root, MAX_D)
    queue ← ∅
    Enqueue(queue, root)
    while ¬ IsEmpty(queue) do
        node ← dequeue(queue)
        model ← GetModel(node)
        if (¬ Correct(model)) and (GetDepth(model) < MAX_D) then
            error ← PickError(model)
            fixes ← GenerateFixes(error)
            childrenNodes ← GenerateNodes(node, fixes)
            EnqueueAll(queue, childrenNodes)
        else if Correct(model) then
            PrintSolution(model) //A solution has been found
        else
            //MAX_D reached
        end if
    end while
end function
```

### 4.3.3. Avoiding Duplicate Effort

This algorithm may satisfy all the required properties, but it is not very efficient. A particular weakness is that two different nodes may in fact represent the same model, obtained through different steps. Figure 4.19 illustrates this scenario. `R` is the root, and `N3` and `N4` are identical models. The former is obtained by applying fix `a` and then fix `b`, whilst the latter is obtained by applying fix `b` and then fix `a`. The problem in this case is that, if `N3` and `N4` are not correct, the search for solutions will be duplicated. Instead, both nodes could be merged into a single one. This can be easily achieved by slightly modifying the algorithm. The updated algorithm is Algorithm 9. Whenever a new node is created, it is compared with the list of existing nodes. If the new node represents a

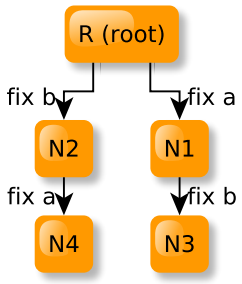



**Figure 4.19.:** Duplicate changes in fixing

model identical to the model of another node, then the new node is discarded. Note that the function `GenerateNode` is similar to the function `GenerateAllNodes` described earlier, but only takes one fix as its second argument, and only returns one node.

**Algorithm 9** Size-limited, no duplicate models, BFS implementation of the model fixing algorithm

```
function FixModel(root, MAX_D)
    queue ← ∅
    Enqueue(queue, root)
    nodes ← ∅
    Append(nodes, root)
    while ¬ isEmpty(queue) do
        node ← Dequeue(queue)
        model ← GetModel(node)
        if (¬ Correct(model)) and (GetDepth(model) < MAX_D) then
            error ← PickError(model)
            list ← GenerateFixes(error)
            for all fix in list do
                newNode ← GenerateNode(node, fix)
                if ¬ Contains(nodes, newNode) then
                    Append(nodes, newNode)
                    Enqueue(queue, newNode)
                end if
            end for
        else if Correct(model) then
            PrintSolution(model) //A solution has been found
        else
            //MAX_D reached
        end if
    end while
end function
```

This solution is still correct, as the update in the algorithm does not affect the correctness of fixes. It is still complete, since only identical nodes are merged. It still terminates, as there will be *fewer* nodes generated.

## 4.4. Solutions Ordering

The above algorithm will produce the set of *all* the possible changes made of a designer-defined maximum number of fixes. That set may be large, especially on large models with many errors. It is therefore important to order the generated solutions to help the designer select the most appropriate solution. What the "best" solution is will of course depend on the DSML being used, and ultimately will come down to the designer's specific requirements. However, it is still possible to provide some ordering that will put the solutions most likely to be selected at the top. Three ordering strategies have been identified. They can be used independently, or combined together: the cost of fixes, the type of changes, and the location of changes. In this section, each strategy is first described and then applied to `rbacDSML`.

### 4.4.1. Number of Fixes

The number of fixes is the simplest way of sorting the solutions, and it is independent of the DSML used. It simply sorts solutions depending on the number of fixes they contain, i.e. the length of the path between the root and the correct model for each solution in the solution tree. The solution with the smallest number of fixes will come first, and the solution with the largest amount of fixes will come last. The idea is that the designer is likely to select a solution that is not too different from the original model over another solution that differs more widely from the original model. This is also the order in which, by definition, the BFS strategy will generate solutions.

However, this strategy is not perfect. It treats all the fixes equally, regardless of how many changes a fix contains. Therefore, this strategy will not necessarily sort the solutions from the one that produces a model closest to the original to the one that produces a model furthest from the original in terms of the number of changes. It does, however, provide an approximation that might be good enough in some cases.

### 4.4.2. Cost of Fixes

The cost of fixes is a refinement of the number of fixes approach to sorting the solutions. Instead of using the number of fixes, it uses the cost of a solution. The cost of a solution is simply the sum of the costs of each fix: $\forall S = \{f_1, \ldots, f_n\}\ scost(S) = \sum_{i=1}^{n} fcost(f_i)$. Compared to the BFS strategy, this one has the advantage of being more precise: the cost of each fix will be considered. However, it requires the DSML developer to specify the $fcost()$ functions.

### 4.4.3. Type of Changes

The third strategy consists of ordering solutions according to the types of changes that are part of it. It is different from using the cost strategy with a $ccost()$ function that returns a different cost for different changes. Instead, it is about classifying solutions in categories depending on the changes it contains. Changes can be the addition or deletion of a node, or the addition or deletion of an edge. In some DSMLs such as `rbacDSML`, this is an important distinction: adding new roles or permissions may in some cases be out of the question, but reorganising some assignments may be more acceptable. Ordering solutions by type of changes allows the designer to focus his attention in priority on the solutions that include the changes that he finds most acceptable, whilst ignoring those he does not necessarily approve of.

### 4.4.4. Location of Changes

The last strategy classifies solutions according to "where" the changes are made. Some DSMLs such as `rbacDSML` define models that are made of several "parts" or "locations". These can be the type of diagram or elements where the changes are made, or, like in `rbacDSML`, a domain-specific distinction such as the difference between the *policy*, the *configuration* and the *scenarios*. Each solution can be classified in one or several of these categories, a choice that is made by the developer. It then comes down to the designer to choose which categories he wants to focus on, and which ones he wants to ignore.

### 4.4.5. Ordering `rbacDSML` Models Solutions

`rbacDSML` is an interesting case study for the ordering of solutions, because it has three clearly identified, domain-specific "locations": the *policy*, the *configuration* and the *scenarios*. These locations can be used to classify the solutions according to their location.

Within a category, it is possible to sort the solutions according to their cost. In `rbacDSML`, the cost of adding a new node is arguably higher than the cost of adding or deleting an edge (there is no deletion of nodes in `rbacDSML`, as it would violate the minimal fix principle). It is then possible to define the cost of a change as follows. If we consider $c_n$ as the addition of a node, and $c_e$ the addition or deletion of an edge, we can define: $\forall c_n,\ ccost(c_n) = 2$, and $\forall c_e,\ ccost(c_e) = 1$. These values can of course be adapted by the designer if necessary.

In addition to a categorisation by location and the cost-based ordering within categories, a *filter* can be defined that shows or hides solutions. The filter comes *after* the solutions generation and ordering, and is useful for the designer to only see the solutions he wants, based on his own criteria, such as whether or not a solution includes the

addition of new nodes. This does make sense in `rbacDSML`: users, roles, permissions and resources may very well be a given, and the designer may decide that he does not want to see solutions that include node additions, or that he does not want to give them priority.

## 4.5. Improvements

The approach for fixing models described in the previous section may be slow, especially on large models with lots of errors. It is a great generic solution that applies to any DSML, but if one is prepared to make use of specific properties of the DSML they are using, the algorithm can be made much more efficient. In this section, several approaches are described that aim at reducing the completion time of the algorithm, or at finding the best solutions faster. The improvements can be used individually or together, and include the prioritisation of error fixing; the elimination of some specific changes; and the search for good solutions in priority.

### 4.5.1. Error Prioritisation

An error arises when an instance of an OCL constraint returns *false*. It has also been discussed in Chapter 3 that dependency relationships can be defined between OCL constraints, and used to more efficiently evaluate a model against a set of constraints.

A similar approach can be taken for the generation of solutions. When selecting which error to solve, the algorithm could be adapted to take those dependencies into account. If there is a dependency between constraint `A` and constraint `B` such that the result of the evaluation of `B` is only meaningful when `A` evaluates to *true*, then it should generate fixes for `A` first. This will avoid the exploration of some unnecessary branches, by making sure that only *actual* errors are fixed.

This approach can be easily implemented by adapting the function that selects the next error to fix, but it assumes that the dependency graph for the OCL constraints has been provided by the DSML developer.

### 4.5.2. Elimination of Undesirable Solutions

Sometimes, while designing his model, the designer *knows* that there are some changes he is not willing to perform, either because he does not want to or because he actually cannot. He may not be willing to add any role in a `rbacDSML` model. He may not be willing to change any of the scenarios. He may not want to remove a particular user-role assignment. Or any other requirement that defines certain solutions as unsatisfactory. Yet, in ignorance of those requirements, the approach described above will explore those unsatisfactory solutions anyway. This is a waste of time and computing resources, as the designer already knows that he will not implement such a solution. Therefore, providing the designer with a way of describing the changes he does *not* want to perform, and adapting the algorithm to take them into account and not waste time exploring those options, could be a huge time saver.

One way for the designer to express which elements he does not want to see changed and in what way is through the use of annotations - or, in UML language, through a profile. This section proposes a set of annotations to attach to elements and associations, and defines `NoChangeUML`, a UML profile that implements these annotations. Of course, the profile can be adapted to other modelling languages than UML, as long as they provide some sort of annotation mechanism.

The annotations provided by such a language include, but are not necessarily limited to, the following:

- an association cannot be deleted;

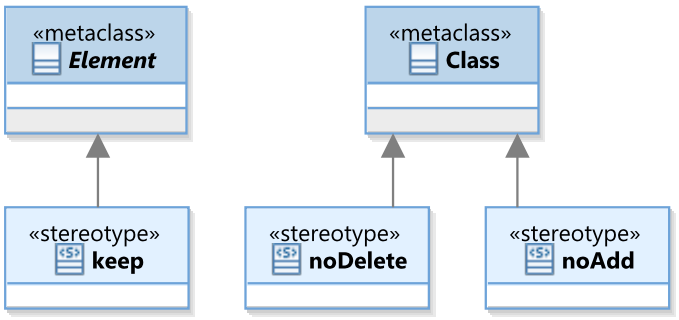



**Figure 4.20.:** UML meta-model extension defining the `NoChangeUML` profile

- an element cannot be deleted (this never happens with `rbacDSML` anyway, but another profile may need it);
- no association can be added to an element;
- no association can be removed from an element.

Figure 4.20 defines the UML profile that provides those annotations. The «`keep`» stereotype can be attached to an association, a class or any other element to make sure that it is not deleted; the «`noAdd`» stereotype can be attached to an element, to make sure that no new association will be attached to that element; and the «`noDelete`» stereotype can be attached to an element, to make sure that no existing association will be detached from that element. This is, in fact, a shortcut to adding «`keep`» to all the associations that have the element as one end.

This set of annotations can of course be extended to support more fine-grained annotations that depend on the DSML considered. For example, it is possible to extend `NoChangeUML` into `NoChangeRbacDSML` to support `rbacDSML`-specific annotations, as expressed in Figure 4.21. The «`noAdd`» and «`noDelete`» stereotypes still exist, but other, more precise stereotypes have also been defined: «`noAddRole`», «`noAddResource`», «`noAddPermission`», «`noDeleteRole`», «`noDeleteResource`», and «`noDeletePermission`». Table 4.1 provides a succinct description of each stereotype's purpose.

**Table 4.1.:** Summary of the stereotypes defined in NoChangeRbacDSML

| stereotype | attached to | description |
|---|---|---|
| «keep» | Element | element or association cannot be deleted |
| «noAdd» | Class | no new association can be attached to the element |
| «noDelete» | Class | no existing association can be detached from the element |
| «noAddRole» | Class | no role assignment association can be attached to the element |
| «noAddResource» | Class | no resource assignment association can be attached to the element |
| «noAddPermission» | Class | no permission assignment or requirement association can be attached to the element |
| «noDeleteRole» | Class | no role assignment association can be removed from the element |
| «noDeleteResource» | Class | no resource assignment association can be removed from the element |
| «noDeletePermission» | Class | no permission assignment or requirement association can be removed from the element |

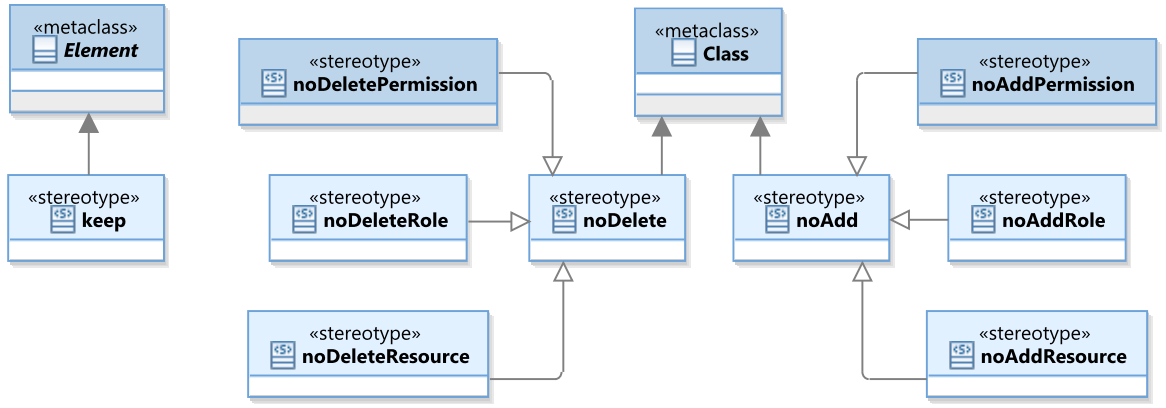



**Figure 4.21.:** UML meta-model extension defining the `NoChangeRbacDSML` profile

### 4.5.3. Searching for Good Solutions First

The algorithm presented in Section 4.3 has been designed with the assumption that the algorithm runs to discover all the possible solutions, then returns them, and they are all displayed to the designer at the same time, after possibly being sorted according to the sorting strategies described in Section 4.4. The order in which the solutions are explored therefore does not matter.

One may however improve the designer's experience by displaying solutions as they are discovered. The main advantage of this approach is that the designer would see the first generated solutions much more quickly, and if he finds one that suits him, might even decide to stop the algorithm before all other solutions have been explored.

However, the order in which solutions are explored becomes important. In other words, it may make more sense to use a more sophisticated approach than a FIFO queue or a LIFO stack to select which node to analyse next while constructing the solutions tree. Several heuristics can be defined to choose which path to explore in priority. These include the number of errors, the reduction of errors, or the cost of a partial solution. These can be easily implemented by using Algorithm 9 with a priority queue instead of a FIFO queue. Each heuristic will then be implemented by a different key computation

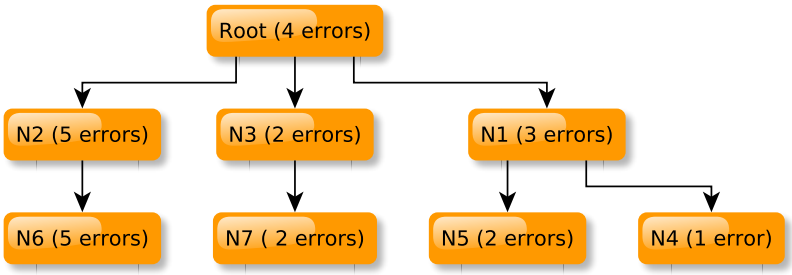



**Figure 4.22.:** Number of errors in intermediate nodes

algorithm for the nodes to insert in the queue. Four heuristics are discussed in this section. It is also possible to combine several heuristics together.

### Heuristic 1: Number of Errors

The first heuristic is fairly simple. Instead of following a BFS or DFS ordering, one could select, from the set of incorrect model nodes, the one with the smallest number of errors. The idea behind this heuristic is that models with less errors are likely to be closer to a correct state, and should therefore be explored in priority. However, this heuristic only selects a local optimum, which will not necessarily lead to the best solution: a good solution could involve an increase in the number of errors at some point on its path, and would then be discarded by the heuristic.

Figure 4.22 shows an example of a fictional model. The number of errors is displayed next to each incorrect node. We are in the situation where all the nodes have already been generated, and we need to select one of the leaves to continue fixing errors. Node $N4$, which has the smallest number of errors, is the one that will be selected.

This heuristic can be expressed as follows, provided that $N$ represents the set of incorrect leaf nodes in the tree under construction:

$$select1(N) = n_x | error(n_x) = min(error(n_0), error(n_1), \ldots, error(n_s)),$$
$$where\ \{n_0, n_1, \ldots, n_s\} = N\ and\ x \in \{0, \ldots, s\}$$

### Heuristic 2: Reduction of Errors

The second heuristic is similar to the previous one, but instead of looking at the number of errors in a node, the algorithm looks at the difference between the number of errors in the parent node and the number of error in the node considered. This way, priority is given to those nodes that represent models that come closer to a correct state.

The reduction of errors can be expressed as follows, for any $n$ representing an incorrect leaf node (except the root of the tree): $red(n) = errors(parent(n)) - errors(n)$. The heuristic can then be expressed as:

$$select2(N) = n_x | red(n_x) = max(red(n_0), red(n_1), \ldots, red(n_s)),\ where$$
$$\{n_0, n_1, \ldots, n_s\} = N\ and\ x \in \{0, \ldots, s\}$$

### Heuristic 3: Cumulative Cost

The third heuristic considers the cumulative cost of each node. It simply selects the incorrect leaf node with the lowest $fcost(node)$. This guarantees that the cheapest partial solution is selected. Assuming that solutions that are closer to the original model are generally preferable, this is a sound strategy. However, a solution higher up in the tree will be more likely to be selected: as it has fewer fixes, $fcost()$ is also likely to be lower. Therefore, in practice, this heuristic will only be a small improvement over the BFS approach. The heuristic can be expressed as:

$$select3(N) = n_x | fcost(n_x) = min(fcost(n_0), fcost(n_1), \ldots, fcost(n_s)),\ where$$
$$\{n_0, n_1, \ldots, n_s\} = N\ and\ x \in \{0, \ldots, s\}$$

#### Heuristic 4: Average Cost

In order to address the potential shortcomings of the previous heuristic, one could use the average cost per node of a path, instead of the cumulative cost. Therefore, short paths would be less likely to be preferred over longer ones, as long as the latter have an average cost by node that is smaller than the former's.

The average costs of errors can be expressed as follows: $acost(n) = fcost(n)/length(root, n)$, where $length(root, n)$ is the length of the path between the root of the tree and the node $n$. The heuristic can then be expressed as:

$$select4(N) = n_x | acost(n_x) = min(acost(n_0), acost(n_1), \ldots, acost(n_s)),\ where$$
$$\{n_0, n_1, \ldots, n_s\} = N\ and\ x \in \{0, \ldots, s\}$$

#### Combining Heuristics

It is of course possible to combine heuristics into new ones. For example, the number of errors and the cumulative cost could be used together to decide which node to analyse next. The score of a node could be computed using a function such as $k_v v + k_{fc} fc$, where $k_v$ and $k_{fc}$ are constant weights, $v$ the number of errors, and $fc$ the cumulative cost. The node with the lowest score could then be selected.

## 4.6. How to Present Solutions

Once the solutions have been generated, they need to be returned to the designer in a meaningful way. The designer must be able to easily identify what each solution consists of, which problems it solves and which elements have been modified.

In Section 4.4, the order in which the solutions should be presented to the user has already been discussed. This section, therefore, focuses on how to represent individual solutions. Designers should be able to visualise each proposed solution individually.

There can be a textual as well as a graphical representation of a solution. They would include the following information:

- the number and the list of errors in the original model;
- the number of fixes, and the number of changes;
- the list of fixes that lead to the correct model;
- the locations where changes have been made.

With the graphical representation, it is also important to show to the user a diagram that highlights the differences between the original model and the correct model. Change description systems, such as UMLChange [50], can be used in this context.

The «`addition`» stereotype can be attached to the elements or associations that have been added to the original model, whilst the «`remove`» stereotype can be attached to the elements or associations that have been removed from the original model. This is sufficient to represent all changes, since a change is either an addition or a deletion.

Once the original model has been annotated with UMLChange, its graphical representation is a matter of choice to be made by the developer of the tool. One could simply display the model with the UMLChange stereotypes, or one could also colour the elements and associations depending on the stereotypes attached (e.g. additions in green and deletions in red).

Currently, the graphical interface to UMLChange has not been implemented. Only a textual representation has been implemented. Once the algorithm has stopped, and if it has found at least one solution, it will present a list of all the possible solutions, in

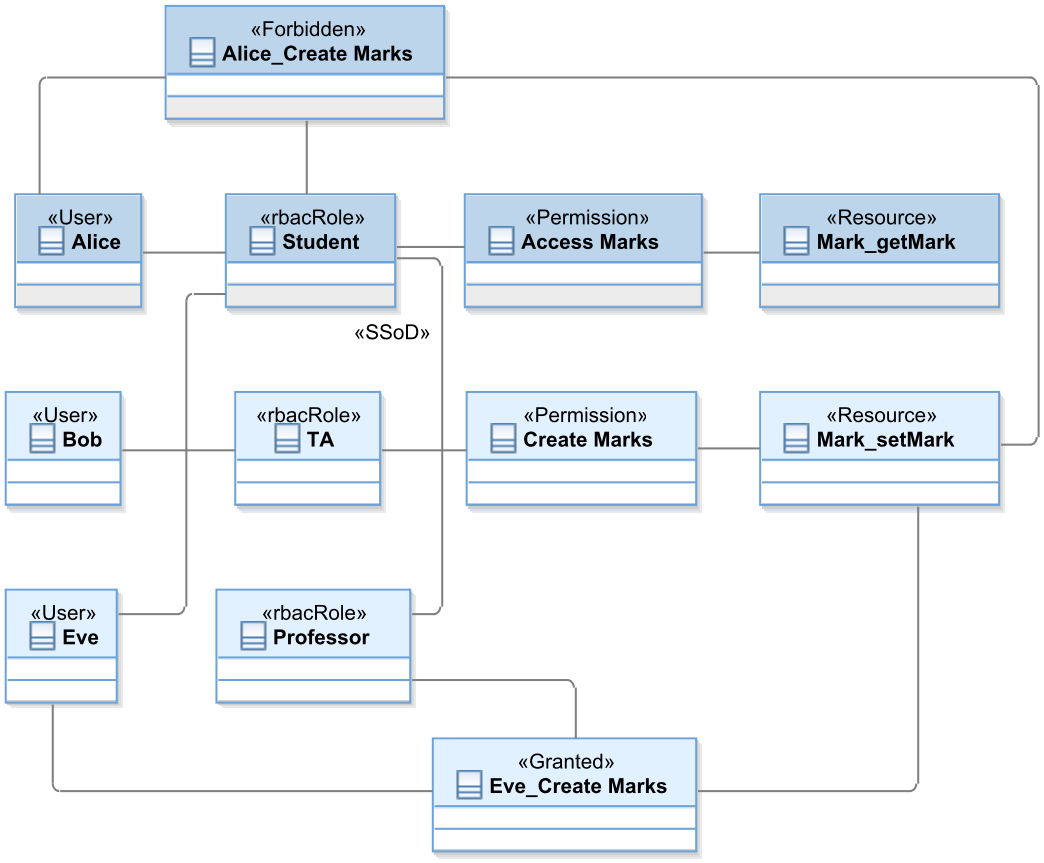



**Figure 4.23.:** An incorrect `rbacDSML` model

the order in which they have been found. Each solution is itself made of a list of fixes, and each fix is a list of changes. Applying the changes in the order in which they are displayed on the incorrect model will bring it to a correct state. Below is an example that describes two possible solutions for the incorrect model shown in Figure 4.23.

Solution:

```
  Fix is made of 3 changes.
Stereotype association change:  Deletion of an association be-
tween Eve and Eve_Create Marks named null.
Stereotype association change:  Addition of an association be-
tween Eve_Create Marks and Bob named null.
Stereotype association change:  Addition of an association be-
tween Professor and Bob named null.
```

Solution:

```
  Fix is made of 4 changes.
Addition of a Class named Class1 and stereotyped with User.
Stereotype association change:  Deletion of an association be-
tween Eve and Eve_Create Marks named null.
Stereotype association change:  Addition of an association be-
tween Eve_Create Marks and Class1 named null.
Stereotype association change:  Addition of an association be-
tween Professor and Class1 named null.
```

# Chapter 5.

# Tool Support

The features described in Chapters 3 and 4 (except the UMLChange interface that provides a graphical representation of proposed changes to fix a model), as well as a few additional ones, are implemented in the tool described in this chapter. The tool is a suite of plug-ins for the UML modelling IDE, Rational Software Architect (RSA), from IBM. The source code is released under the Eclipse Public Licence (EPL), and is freely available online [4]. The implementation for the evaluation and analysis features is a mix of OCL and Java code.

This chapter is divided into six sections. The first one discusses the choice of developing a plug-in rather than a standalone tool as well as the choice of the platform. The second one examines the implementation details. The third section reports on the experience of working with RSA in particular, and with a modelling platform in general. The following two sections are dedicated to two studies: the first one compares the various options for evaluating `rbacUML` models presented in Chapter 3, and the second one compares the various options for fixing `rbacDSML` models presented in Chapter 4. Finally, the last section presents a real-life case study where we applied `rbacUML` to `ChiselApp`, a web application for hosting and sharing projects with the `Fossil` distributed version control system.

## 5.1. Choosing the Right Platform

In this section, we justify our choice of developing a plug-in for an existing MDE tool, and our choice of RSA as a modelling tool. We elaborate on the reasons behind those choices and on the alternatives that we considered. We then elaborate on the architecture of the selected platform.

### 5.1.1. Plug-In rather than Standalone

At the core of `rbacUML`, is the desire to integrate `rbacUML` as much as possible into designers' existing activities, processes and tools. Since the DSML and DSMAL parts of the `rbacUML` approach are defined as UML profiles, tight integration with existing UML modelling tools was greatly valued. A plug-in seemed to be the right choice, and it was confirmed by a few other considerations. Developing a plug-in would allow to use existing diagramming capabilities, instead of having to implement it ourselves. Since OCL constraints were a big part of the approach, reusing an existing OCL evaluation engine was also a great argument in favour of a plug-in over a standalone tool.

### 5.1.2. Comparing Available Modelling Environments

Once it was clear that a plug-in was going to be developed instead of a dedicated tool, the platform to build it on had to be chosen. Three platforms were selected for evaluation, according to the following list of requirements:

- UML modelling capabilities: the tool must support the UML 2.x standard;
- OCL queries evaluation engine: since `rbacUML`'s analysis capabilities are based on OCL, an efficient and expressive engine, i.e. a full OCL implementation, is a must;
- Support for custom UML profiles: the `rbacUML` DSML and the `rbacDSML` DSMAL are represented as UML profiles, so the ability to define custom profiles and to use them within the platform is crucial;
- UML diagrams creation support: models in `rbacUML` are represented using several types of diagrams: class diagrams, sequence diagrams and activity diagrams. It is therefore essential that the platform allows one to easily create at least those three types of diagrams;

- File format: ideally, the perfect tool should use, or at least allow import from and export to, a standardised file format such as the OMG's XML Metadata Interchange (XMI) format, which is an XML extension;
- UML profile tooling generation: an optional, but highly appreciated feature, is the ability to create tooling palettes in order to make the creation of `rbacUML` models easier;
- Licence: an open source tool would be preferable as it would allow for a broader distribution of our plug-in.

The three tools considered, around 2009 - 2010, were Papyrus, an open-source Eclipse plug-in for UML modelling [39], ArgoUML, an open-source UML modelling software, and IBM Rational Software Architect (RSA), a proprietary UML modelling solution built on top of Eclipse [47]. Table 5.1 provides a comparison of the three platforms for each of the requirements identified. It is clear from the table that RSA was the only platform that seemed to satisfy most of the requirements. The only issue was that it is proprietary software. It was thus selected. While they all have evolved since the comparison was done, our remarks regarding these three tools still hold as these lines are written.

**Table 5.1.:** Comparison of MDE environments

| Name | UML | OCL | UML profile | UML diag. | Tooling gen. | file format | open source |
|---|---|---|---|---|---|---|---|
| Papyrus | √ | √ | partial | buggy | no | XMI | √ |
| ArgoUML | 1.4 only | partial | no | partial | no | zargo & XMI | √ |
| RSA | √ | √ | √ | √ | √ | EMX & XMI | no |

Papyrus was, at the time, still in its early days. Although it was built on solid Eclipse foundations, such as EMF and its associated OCL evaluation engine, the diagramming part provided by Papyrus was quite slow and buggy. In particular, activity diagrams were very unstable and caused frequent crashes. It had to be ruled out, but it has since made a lot of progress.

ArgoUML is the only of the three platforms not to be based on Eclipse. It is a stable product, but only supports UML 1.4, does not support profiles and has limited OCL support. It had to be ruled out as well.

RSA was the last platform considered. Like Papyrus, it is built on Eclipse and uses EMF and the associated OCL evaluation engine. RSA comes as a layer on top of Eclipse, providing different features, the most notable one being a very mature UML modelling and diagram editing environment. Furthermore, RSA was the only tool allowing one to very easily create tooling palettes for our profile. It uses EMX to store models, an XML format that looks very similar to XMI, and allows for export to and import from XMI. Whilst it is not an open source project, IBM has an "academic initiative" programme giving academics free access to its products, including RSA.

The RSA platform is built on top of Eclipse, and makes extensive use of the Eclipse Model Development Tools (MDT) project. It provides many features, but in this section the focus is on those directly relevant to our work.

RSA provides a diagram edition layer on top of Eclipse UML, as well as the ability to define UML profiles and automatically generate code for editors that include said profiles. RSA's extensive use of Eclipse MDT technologies makes UML-related projects developed for RSA relatively easy to port to other Eclipse-based tools that also make use of MDT.

## 5.2. The rbacUML Plug-In

In this section, we describe the implementation of the `rbacUML` plug-in [64], and discuss which Eclipse and RSA technologies the plug-in uses.

### 5.2.1. The Rational Software Architect Modelling Stack

At the bottom of the UML modelling stack is the Eclipse Modeling Framework (EMF), which uses the Ecore meta-model. On top of EMF is UML2, an EMF implementation of the UML 2.x standard using UML. In other words, the UML meta-model is defined using EMF, and Ecore is therefore used as UML's meta-meta-model.

Eclipse also includes an implementation of an OCL engine, also built on top of EMF, allowing one to parse OCL constraints and use them to evaluate EMF models. In the last few years, the Eclipse project underwent an important change in the implementation of the OCL engine, and two separate implementations co-existed for the duration of the transition [27]. The mature OCL meta-model provides a parser and an evaluation engine for both Ecore and UML2 model. It is, however, tightly coupled to Ecore, causing some performance issues and making it difficult to stick to the OCL 2.2 standard. In particular, it makes it very difficult to create and evaluate OCL constraints that work on annotations provided by UML profiles. The new OCL meta-model, called pivot OCL, addresses the shortcomings of the mature OCL meta-model, and complies to the OCL 2.2 standard.

On top of Eclipse MDT comes RSA, which uses the UML modelling and mature OCL meta-model features to provide additional features. The most obvious one is a very efficient UML diagramming capability, allowing one to represent UML2 models as diagrams (class, sequence, activity, etc.) instead of "simply" the trees provided by the Eclipse UML2 project. Another feature is the profile tooling generator, that allowed us

to easily create UML profiles and automatically generate a RSA plug-in to use the profile in UML models.

### 5.2.2. The UML Profiles

Building the UML profiles was the first step in the tool's implementation. We were able to make use of RSA's profile tooling project capabilities, which allowed us to (1) create the stereotypes, specify the types of elements on which they can be attached, and define the associations between the stereotypes, graphically; (2) for each stereotype, specify the appropriate OCL constraints; (3) generate the tooling model and customise it; and (4) generate the tooling code, producing a usable RSA plug-in with a tooling palette allowing designers to directly create stereotyped elements.

#### `rbacUML`, the DSMAL

The `rbacUML` DSMAL has been implemented according to its description in Chapter 3, and contains all the OCL queries in Appendix B. There has been no modification at all.

#### `rbacDSML`, the DSML

The `rbacDSML` DSML, on the other hand, differs slightly from its description in Chapter 3. The reason for the differences comes down to implementation problems, and limitations or bugs of the RSA and Eclipse platforms.

Firstly, instead of associations between stereotypes, UML associations have been used. The reason for this change is that associations between stereotypes are not treated by RSA as "real" UML model elements, which has a few annoying consequences:

- it is not possible to attach stereotypes to associations between stereotypes, making it impossible to annotate fixed models with UMLChange annotations;
- the navigation of associations between stereotypes is unidirectional. Whilst it is possible to navigate them in the opposite direction, it is complex
- the visual representation of the associations between stereotypes is separated from their existence on the model. As a consequence, it is possible to delete an arrow from a diagram without deleting the corresponding association on the model. Similarly, it is possible to add an association without the arrow appearing on the relevant diagrams. This is likely to be a bug in RSA, and does not appear with "real" UML associations.

For these reasons, the stereotype associations have been replaced by UML associations.

Another issue arose from the role hierarchies. The OCL standard provides a transitive closure operator, `closure()`, but only since its version 2.3. RSA having been released before then, it will flatly refuse to even parse an OCL constraint with the closure operator, if it is included in a profile. There is at least one partial workaround to overcome this limitation, but it is not perfect. Fortunately, RSA happily provides the `allParents()` operation, which gives the transitive closure of a Class's superclasses. It has then been decided to represent role hierarchies in this fashion, exactly like it is done with `rbacUML`.

Because of these two changes, the OCL constraints for the `rbacDSML` implementation slightly differ from their description in Chapter 3. The implemented version of the constraints can be found in Appendix A.

### 5.2.3. Visualisation of Large Configurations

Any diagrammatic modelling approach suffers from problems with the visualisation of models with many elements. However, two measures mitigate this problem for `rbacUML`. The first one comes from `rbacUML`'s design, where the RBAC configuration and the business logic are clearly separated and represented on two different diagrams: the access control diagram for the configuration, and a standard class diagram for the business logic, including the annotations that indicate which operations must have their access restricted to authorised users only.

The second one is a visualisation feature we implemented in the plug-in, namely the designer has the ability to select from the model a list of users, roles and permissions, and to transfer them to the access control diagram in one click. Not only will the selected users, roles and permissions appear on the diagram, but so will all the roles assigned to the selected users, all the users, permissions, parents and children of the selected roles, and all the roles assigned to the selected permissions. Through a smaller diagram, it provides a clear picture of the relationships between the selected elements. Since the verification is made on the *model* and not on the *diagrams*, this has no impact on the result of the evaluation of OCL queries.

### 5.2.4. Import from `LDIF`

Often, an organisation will use the same user directory for several applications. This saves a lot of time in user administration, and helps prevent a lot of conflicts and update problems. LDAP and Active Directory are very popular solutions, and both export in the `LDIF` format. `rbacUML` is capable of reading an `LDIF` file to populate a model automatically. Users in the file are mapped to users in the model, while groups in the

file are mapped to roles in the models. If a group A is a member of a group B, then in the `rbacUML` model, A will be a child of B.

It is quite likely that several users in the file will have the same set of groups. They can be regarded as redundant for modelling purposes, and `rbacUML` will suggest to merge them into one single user in the model. Information about all the merged users is kept on the model in order to allow for the `LDIF` file to be regenerated from the model if necessary. Our importer directly translates the content of the `LDIF` file into XML Metadata Interchange (XMI), the format used for representing UML models, and is therefore usable by any UML modelling tool.

### 5.2.5. Selective Evaluation of OCL Queries

We have implemented the selective OCL query evaluation, giving designers full control over which OCL queries to evaluate by simply selecting the queries or categories of queries to evaluate. Designers can also chose if they want to run an ordered evaluation or not. Since our OCL constraints are defined in a UML profile, it is easy for developers to edit the profile in order to add, remove or modify OCL constraints. Their classification in one of the categories that we have defined is done on the basis of the query name: well-formedness queries start with *WF*, verification queries with *VER*, satisfiability queries with *SAT*, coverage queries with *COV*, completeness queries with *COMP*, and redundancy detection queries with *RED*. Therefore, developers can easily place their new or updated query in the category of their choice by giving them an appropriate name. Queries will then automatically be picked for evaluation in the correct category. Currently, it is not possible for developers to create a new category or to change the dependency relationships between categories, unless of course they are willing to modify the tool's source code.

### 5.2.6. Model Generator

Another feature of the `rbacUML` plug-in is the model generator. It has been developed as part of a performance study of the tool. Its purpose is to generate random `rbacUML` models, either correct or incorrect depending on the user's choice, of a specified size. We used it to calculate the evaluation time of increasingly large models, as well as to compare the "full" evaluation of a model with the ordered evaluation.

Unlike the LDIF import filter, the model generator has not been implemented by directly generating XML documents. Instead, we made use of Eclipse UML's features, that allow one to very easily create UML model elements - including stereotypes from an existing UML profile.

### 5.2.7. Fixing Incorrect Models

Finally, the last feature of the tool is the fixing of incorrect `rbacDSML` models. Implemented in Java but using the `rbacDSML` OCL constraints to verify the model, the fixing feature generates solutions to fix incorrect models, as described in Chapter 4. Designers have the opportunity to choose from a selection of traversal strategies as well as constraint selection strategies, to set the maximum height of the solutions tree, and to set the maximum number of solutions to return.

## 5.3. Working with Rational Software Architect

This section contains a discussion of the advantages and disadvantages of working with RSA. The positive aspects are presented as well as the negative aspects, in the hope that it may be useful for developers of DSMLs or DMSALs on top of UML, as well as for further improvements of the platform.

### 5.3.1. The Good

There were many advantages in using the Eclipse platform in general, and RSA in particular, to build the `rbacUML` tool.

#### The Profile Builder

Using the UML profile builder to create `rbacUML` proved to be a huge time saver. Indeed, the ability to define the stereotypes and their associations graphically, but also to use the built-in editor to define the OCL constraints, all without writing a single line of non-OCL code, was a much faster way to develop and test our profile than having to manually write the profile as an XMI document. It also made it very easy to come back to the profile to fix a bug, add a new feature or test several alternatives for a particular construct.

#### The Profile Tooling Generator

The profile tooling generator was probably one of RSA's features that saved us the most time. The ability to generate in one click a tooling palette to help designers create `rbacUML` models, and generate a RSA-based environment dedicated to `rbacUML` were incredibly valuable, as the alternative would have been to write all that code manually. The generator also allows for many parameters to be configured before the code is generated, allowing us to tailor the generated tool to our exact needs and requirements.

#### The OCL Engine

To evaluate OCL constraints, we used Eclipse's OCL validation engine, a much better solution than writing our own engine. Eclipse's OCL engine is very powerful and highly

configurable. RSA even provides a button to evaluate all the OCL constraints associated to a model in a single click, and when we had to dive deeper into the code to write our own evaluation procedure for selective and ordered evaluations, the OCL engine could be configured to do what we wanted it to do.

### Creating UML Elements

Programmatically creating UML elements, but also navigating elements through associations, was greatly facilitated by the Eclipse UML component, which does a great job at hiding the underlying complexity of the model. This provided numerous advantages compared to directly editing the EMX files (like we did for the LDIF import filter), or even the EMF or Ecore representations.

### The Use of Standard Tools and Formats

The fact that both Eclipse and RSA use (mostly) standard technologies and formats was very useful to keep the tool generic enough that it could be ported to other platforms. In fact, the LDIF import filter is even platform-independent: thanks to RSA's usage of the standard XMI format, any tool that also uses XMI can read models created from the filter.

The standard-compliant OCL engine is also worth noting: since it supports the OCL standard, the OCL constraints we wrote can be copied verbatim to another tool with a standard compliant OCL evaluation engine. Furthermore, since RSA uses Eclipse's engine, `rbacUML` should be relatively easy to port to other Eclipse-based tools such as Papyrus.

#### All these Features Come "for Free"

The last advantage of using a plug-in, and RSA in particular, are the features that came "for free" and that didn't have to be implemented: the diagramming capability; the error reporting, in the tree-like model explorer, on the diagrams themselves, *and* in a textual form in a dedicated view; etc.

It would be almost impossible to list all the platform's time saving features. In this section, the most salient positive points have been pointed out.

### 5.3.2. The Bad, and the Ugly

Now the focus is on the less positive parts of the development of `rbacUML` - things that didn't go very well, bugs or difficulties that were encountered. This section is not meant to be understood as criticism towards the tools or the team behind them, but instead, it points plug-in developers to areas they need to pay particular attention to, where they are likely to encounter difficulties, and it provides the platform developers with pointers on how to improve the platform to make third-party developers' work easier.

#### The Profile Tooling Generator

Whilst the profile tooling generator saved huge amounts of time, it is not perfect, and there were situations where it was necessary to dive into the generated code to fix some issues.

The first issue was a bug in the code generation of stereotypes attached to `Action` elements. One of the subtypes of the `Action` type in UML was causing the generated code to produce a very unstable tool. Fortunately the stereotypes applied on `Action` elements didn't really need to be applied on that particular subtype, and it could simply

be removed from the list of elements on which the stereotypes could be applied - and the tooling code could then be regenerated.

The second issue was not a bug, but had to do with the way the code generator works, and with the incremental way we developed the UML profile. Usually we were adding new elements at each iteration, but occasionally we had to delete elements as well, as we realised that a particular RBAC construct could be better or more succinctly expressed with another construct. The tooling code generator works in a quite conservative way, to make sure that user-defined code is not overwritten unless necessary. Therefore, re-running the generator after it has already run at least once will not result in the generator wiping out the existing code and replacing it by its own, but instead, it will only overwrite files that it generates, and leave the others alone. This means that, if an element is *removed*, the implementation of the related features will be left in the code (since they are not generated anymore), and cause compilation problems. It is then the users' responsibility to go through all the compilation errors and remove the now useless classes and references to elements that do not exist anymore. This is a problem we are trying to solve using bidirectional transformations to synchronise user changes with the generated models [114].

### Bugs

We encountered a few annoying bugs in the platform, that forced us to develop workarounds and/or dive into the lower layers of the platform. In particular, known bugs in the OCL evaluation engine made it more difficult to navigate associations between stereotypes. Furthermore, parts of the evaluation engine couldn't actually deal with OCL queries that returned non-boolean values, even though the documentation indicates otherwise. This prompted us to rewrite these queries so they would return boolean values, or to use a lower level of abstraction to get around the problem.

There were also bugs that made it impossible to navigate stereotype associations in Java using the UML abstraction level, and we had to use the underlying representation.

### The Size of the Platform

The Eclipse platform is *huge*, and so is the RSA platform. Combined, they form a gargantuan set of technologies, built to work on top of or in combination with each other. While this obviously provides immense benefits, it also comes with its faults and weaknesses. It can be very difficult and intimidating for developers that are new to the platform to get a working understanding of how all the pieces fit together. RSA includes some documentation, which frequently refers to the Eclipse documentation, but dead links are not uncommon. Furthermore, the IBM academic initiative does not include any support from IBM or Rational, so we were left on our own to figure out how the platform works and what its limitation are, only with the help of the documentation, which is often incomplete. We also used the community support, via the IBM forums or websites such as Stackoverflow [105], but got very few (if any) answers on some of the most advanced questions. It seems that there is not a massive community of advanced OCL users, or if it exists, we have yet to find it.

Learning how to use the platform requires a large time investment, especially for developers that do not have an Eclipse/RSA expert handy. We had to learn about the Eclipse platform, about plug-in development for Eclipse, about the Eclipse MDT project and its limitations, and about RSA. We then had to put all that information together and figure out how these projects relate to each other. It took us months, and we are still learning every day. We are documenting our experience to make it easier for the community to develop similar modelling plug-ins for the Eclipse or RSA platforms.

#### Limitations to Dissemination

Our choice of RSA as a platform did most probably limit the potential for dissemination of `rbacUML`. Indeed, whilst RSA is available for free to academics, few are willing to make the effort to deploy it, most notably because of the rather large amount of online paperwork to fill, the obligations that come together with the IBM academic initiative, and the lack of support for Mac OS X (although there is now a preview version of RSA 8.5 for Mac OS X). Non-academics were understandably reluctant to invest in costly RSA licence fees, which made it very difficult to reach out to industry.

In order to mitigate this issue, we tried to avoid using RSA-specific APIs as much as possible, and instead try to rely on Eclipse MDT alone whenever possible. We have been much more successful at this with our most recent developments, and one of the added benefits is that there is less documentation to deal with. While currently RSA is still required to run our plug-in, we hope that, by further diminishing our reliance on IBM's proprietary APIs, and thanks to the progress of open-source tools such as Papyrus, we will be able to migrate to a fully open source platform in the near future, which will doubtlessly make it easier for third parties to use, and perhaps contribute to or build upon our plug-in.

### 5.3.3. Discussion

This section has focused on the implementation of the `rbacUML` approach. The choice of implementing the tool as a plug-in of an existing MDE platform was quite straightforward as it allowed for a very tight integration of our approach with existing practice. From the experience reported above, the following suggestions can be derived to help individuals or organisations willing to take on a similar route.

- **Plug-Ins** are definitely the way to go to achieve excellent integration very quickly. The amount of time saved by the ability to reuse existing components is perhaps the best argument in favour of using a plug-in;
- If interoperability is a concern, one should be very careful about the platform's support of **standards**;
- Sufficient **time** will have to be allocated to acquire in-depth knowledge of the platform. Even the lower layers may have to be used to get around bugs and problems;
- If the tool is meant to be used by a large public, the platform must be carefully chosen to make it as easy as possible to adopt.

Overall, the `rbacUML` experience has been positive, and further development is under way to integrate the `rbacUML` approach even more with designers' MDE workflow.

## 5.4. `rbacUML` Evaluation Performance

In order to assess the scalability of `rbacUML`, we measured the query evaluation time. We focused on four variables: the size of the model (the number of elements + the number of associations), the result of the evaluation (success or failure), the usage of our ordered evaluation and/or selective evaluation approaches, and the usage of parallelised evaluation for categories of queries that have the same dependencies.

For the first variable, we wrote a model generator that can generate random and correct models (i.e. models that pass all well-formedness and verification queries) of a specified size. The generator is available online with the `rbacUML` plug-in [4]. It allows one to create `rbacUML` models in both the `XMI` and the `EMX` formats. The user provides an XML file that describes the size of the model he wants to generate. Several parameters

can be set, such as the number of users, roles, permissions, «`Restricted`» operations, «`Granted`» and «`Forbidden`» actions, etc. Ranges can also be provided for each type of association, e.g. one can specify that each user should have between 3 and 10 roles. The generator user can simply use the sample XML configuration file available on the website [4] and adapt it to his needs. Using that XML file, the generator tries to generate a model that satisfies the user's requirements. Due to implementation constraints and in order to keep the generation time to a minimum, it can happen that the number of elements or associations will be a bit lower than specified. The generator does however provide the number of elements and associations actually created. By default, the generator will create models that pass both the well-formedness and the verification queries. An example of a generated model is available in Section C.1 of the appendix, together with an example XML configuration file used for the generation of the model.

One may wonder how realistic those auto-generated models are. We have encountered anecdotal evidence that access control models generally contain a large number of users (depending on the organisation's size), but many less roles, for example. Since the model generator allows us to set the number of elements of each type, we have tried to match these numbers with real access control policies we have encountered. However, the degree of realism of our auto-generated models is not really a threat to the validity of this analysis. Indeed, what we are looking at is the impact of the selective and ordered evaluations on the total evaluation time. Therefore, we compare several ways of analysing the *same model*, and the results are interesting even if said models are not realistic. Similarly, one will notice that the auto-generated models may contain lots of «`Granted`» scenarios, but very few «`Forbidden`» ones. Again, this is not an issue at all: since the OCL constraint used for verifying «`Forbidden`» scenarios is simply the negation of the OCL constraint used for verifying «`Granted`» scenarios, the type of scenario has very little influence on the verification performance.

The evaluation was performed on a Linux system with an Intel Core i5 CPU at 2.53GHz, with 4GB RAM, using IBM RSA v8.0.4. Each measurement has been taken three times, and we have selected the fastest one, in order to minimise the disruption created by the scheduler and other running applications. For each model size, we have generated 5 random models, and used the average evaluation time. Detailed tables of the evaluation times are described in Appendix C.1, and the entire evaluation data, including the generated models, is available online with the `rbacUML` tool and the model generator [4].

We have also computed the number of reported errors and warnings, to compare how our proposed improvements affect the number of reported problems. These have been computed once for each model, and the average of the 5 models of comparable size is reported. Our aim was to show how many errors and warning are reported, and how to reduce their number to make it easier for the designer to act on the meaningful ones.

The OCL query validation service in RSA works as follows. There is a set of OCL queries that are registered with the validation service, which includes `rbacUML`'s queries. One can define a filter that will select the queries to be evaluated. Then the evaluation service is called with said filter and a collection of UML elements on which the queries will be run. The evaluation service then returns the result.

### 5.4.1. Evaluation of each Type of Query

We broke down the evaluation into several phases, each one evaluating a particular category of `rbacUML` OCL queries discussed in Chapter 3. Figure 5.1 shows the evaluation time for models of increasing size. As we discussed in Chapter 2, in Egyed's work on incremental evaluation of OCL constraints, the larger industry models involved "tens-of-thousands" of elements [28], so our evaluation goes up to the lower end of that order of magnitude.

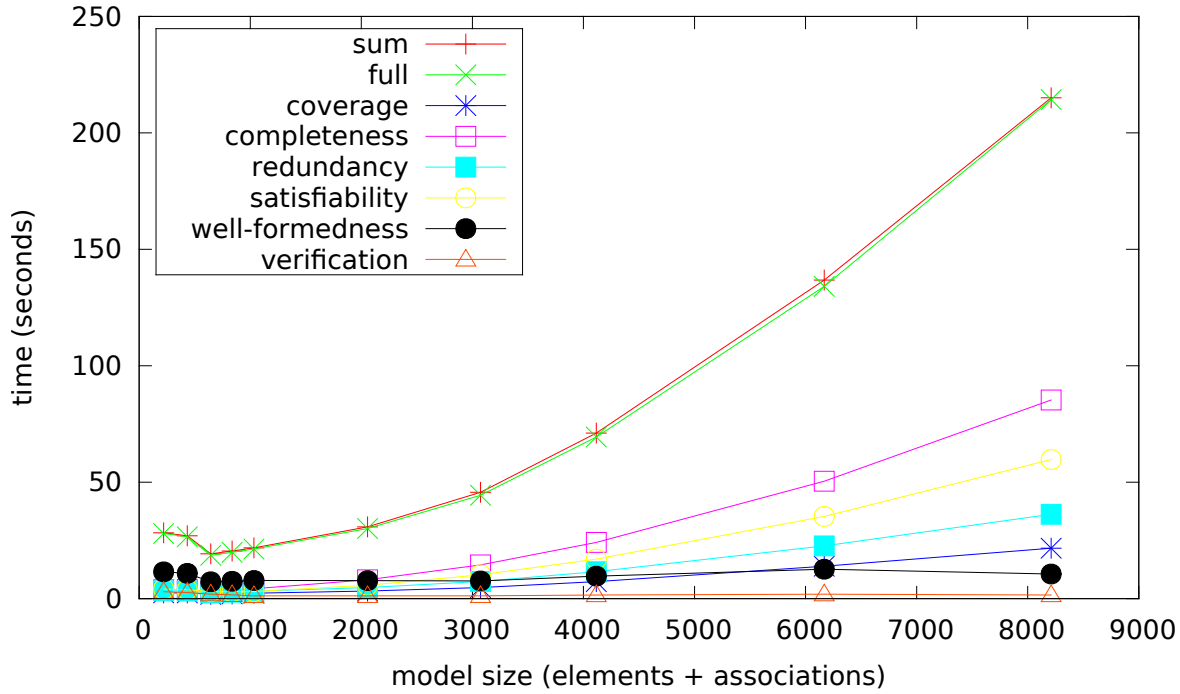



**Figure 5.1.:** Evaluation time (in seconds) for models of increasing size, broken down by OCL query category, and compare to the full evaluation time

There is one curve for the evaluation of all the constraints in one single call to the evaluation service, called *full*. There is also one curve for the evaluation of each category of OCL queries, called *WF*, *VER*, *SAT*, *COV*, *COMP* and *RED*. Finally, the *sum* curve is the sum of the evaluation times of each category individually. It differs from *full* in the number of calls to the evaluation service: while *full* evaluates all the constraints in one go, *sum* is the sum of the evaluation of each category individually.

Several observations can be made. First, the well-formedness and verification queries are evaluated quite quickly compared to the other types of queries. This is good news, as they are the most important ones to the designer. Indeed, designers are likely to be willing to keep a close look at whether their model is syntactically correct, and whether it passes the scenarios they have modelled in the Activity diagrams. The other constraints, while important, merely provide analysis on the quality of the model - its completeness, coverage, redundancy and satisfiability. One could easily imagine having designers

regularly evaluate well-formedness and verification queries on their development platform, while leaving the other types of constraints to a server, e.g. as part of a continuous integration process, where the time and memory required for their evaluation is less of a problem. Another observation to be made is that the overhead cost of evaluating each type of query separately is almost zero, as one can see by comparing the *full* and *sum* curves.

### 5.4.2. Correct v. Incorrect Models

The next step was to compare the evaluation of correct and incorrect models. We used the model generator to generate three types of models: correct models, that do not raise any errors or warnings for their well-formedness and verification queries; malformed models, that do raise errors for their well-formedness queries; and incorrect models, that do not raise any errors or warnings for their well-formedness queries, but that do raise errors for their verification queries.

To generate malformed models, the model generator assigns roles to activity partitions that have not been assigned to the corresponding user, breaking one of the well-formedness queries. To generate incorrect but well-formed models, we simply took correct models, and changed all the «`Forbidden`» stereotypes into «`Granted`» stereotypes, as well as all the «`Granted`» stereotypes into «`Forbidden`» stereotypes. Since the original models were correct, the actions stereotyped with «`Forbidden`» were guaranteed to require at least one permission that was not activated by the user. Since the actions have been stereotyped with «`Granted`» instead, this guarantees that the corresponding verification query fails. Similarly, the actions originally stereotyped with «`Granted`» were guaranteed to succeed, and therefore all the required permissions were available to the user. When the stereotype has been changed to «`Forbidden`», the verification query fails, since there are no permissions missing.

**Table 5.2.:** Number of warnings raised in each category for increasingly large correct models

| **correct** | 250 | 500 | 750 | 1000 | 1250 | 2500 | 3750 | 5000 | 7500 | 10000 |
|---|---|---|---|---|---|---|---|---|---|---|
| completeness (**W**) | 0 | 0 | 0 | 0 | 1 | 1 | 2 | 4 | 5 | 7 |
| coverage (**W**) | 10 | 20 | 32 | 46 | 59 | 122 | 185 | 243 | 365 | 490 |
| redundancy (**W**) | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **total (W)** | 10 | 20 | 32 | 46 | 60 | 123 | 187 | 247 | 370 | 497 |

In Figure 5.2, we compare, for each type of model, the total evaluation time for a full evaluation and for an ordered evaluation. While the full evaluation results are similar across the three graphs, the ordered evaluation times vary. Indeed, on a correct model, the ordered evaluation will first evaluate the well-formedness constraints. No errors or warnings will be raised so the verification, coverage, completeness and redundancy constraints will be evaluated. Since the verification constraints do not produce any errors or warnings, the satisfiability constraints are not evaluated. The result is an evaluation time slightly below the full evaluation time, as all types of queries but the satisfiability queries are evaluated. The incorrect models evaluation is similar to the correct evaluation, except that, since the verification fails, the satisfiability constraints are evaluated too. The ordered evaluation time is therefore the same as the full evaluation time. The malformed models evaluation is quite different. With the ordered evaluation, when the well-formedness evaluation fails, no other types of queries are evaluated, which leads to a significant improvement on evaluation time compared to the full evaluation. Therefore, the ordered evaluation is never slower than the full evaluation, and in some cases, it is significantly faster.

Table 5.2 shows the number of errors and warnings raised for each size of model, broken down by OCL query category, for correct models. Tables 5.3 and 5.4 do the same for malformed and unverified models.

In Table 5.2, we have ignored well-formedness, verification and satisfiability constraints. Indeed, since the models are correct, they will not raise any errors or warnings in these

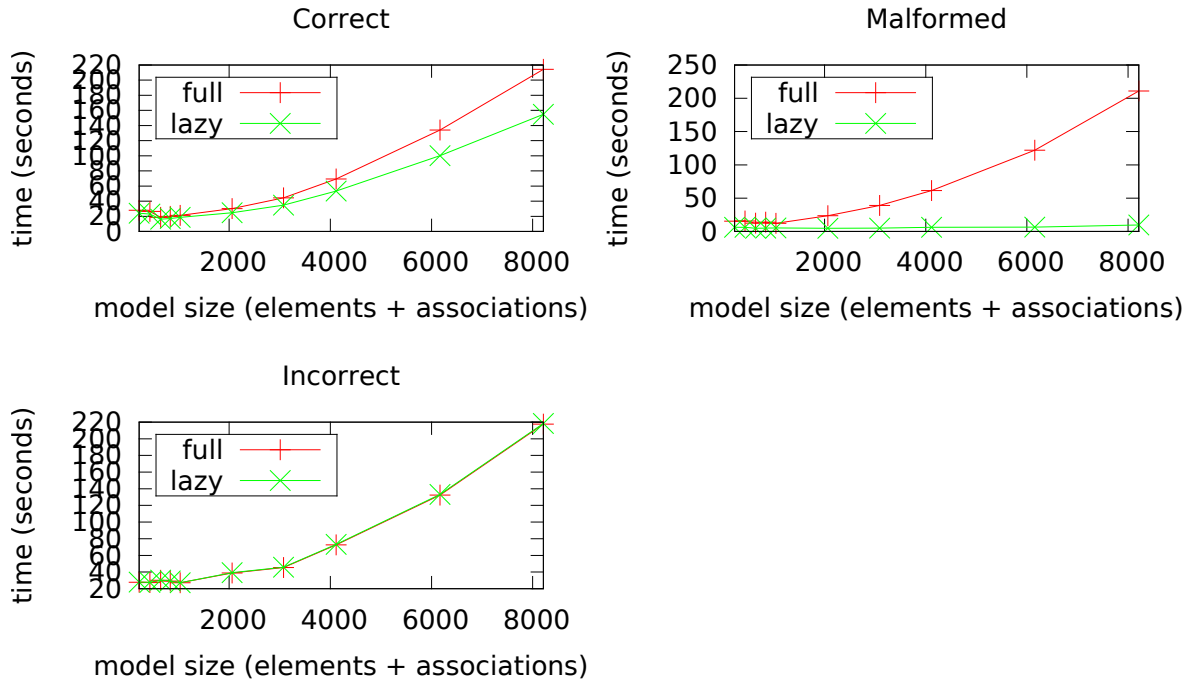



**Figure 5.2.:** Evaluation time (in seconds) for correct and incorrect models of increasing size (see Tables C.1, C.2 and C.3 in Appendix C.1 for actual numbers)

**Table 5.3.:** Number of errors/warnings raised in each category for increasingly large malformed models

| **malformed** | 250 | 500 | 750 | 1000 | 1250 | 2500 | 3750 | 5000 | 7500 | 10000 |
|---|---|---|---|---|---|---|---|---|---|---|
| well-formedness (**E**) | 1 | 2 | 3 | 2 | 2 | 3 | 3 | 3 | 2 | 3 |
| verification (**E**) | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| satisfiability (**W**) | 3 | 13 | 21 | 41 | 64 | 143 | 223 | 300 | 450 | 600 |
| completeness (**W**) | 0 | 0 | 1 | 0 | 0 | 2 | 3 | 3 | 5 | 6 |
| coverage (**W**) | 9 | 21 | 33 | 47 | 59 | 118 | 181 | 241 | 369 | 489 |
| redundancy (**W**) | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **total (E/W)** | 1/13 | 2/34 | 3/55 | 2/88 | 2/123 | 3/263 | 3/407 | 3/544 | 2/824 | 3/1095 |

**Table 5.4.:** Number of errors/warnings raised in each category for increasingly large unverified models

| **unverified** | 250 | 500 | 750 | 1000 | 1250 | 2500 | 3750 | 5000 | 7500 | 10000 |
|---|---|---|---|---|---|---|---|---|---|---|
| verification (**E**) | 5 | 15 | 22 | 24 | 25 | 50 | 75 | 100 | 150 | 200 |
| satisfiability (**W**) | 3 | 14 | 25 | 42 | 64 | 146 | 223 | 300 | 450 | 600 |
| completeness (**W**) | 0 | 0 | 0 | 0 | 1 | 1 | 2 | 4 | 5 | 7 |
| coverage (**W**) | 10 | 20 | 32 | 46 | 59 | 122 | 185 | 243 | 365 | 490 |
| redundancy (**W**) | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **total (E/W)** | 5/13 | 15/34 | 22/57 | 24/88 | 25/124 | 50/269 | 75/410 | 100/547 | 150/820 | 200/1097 |

categories. For the same reason, we ignored the well-formedness category in Table 5.4, since the models are well-formed.

It is quite clear that, even on relatively small models, the number of errors, and especially the number of warnings, goes up very quickly. This is partly due to the fact that the models are generated randomly, as we have discussed earlier.

### 5.4.3. Discussion

It appeared from the above evaluation that evaluating the entire set of `rbacUML` OCL queries has a more-than-linear complexity with regard to the size of the model, and that the number of errors and warnings produced grows quickly too. Breaking down the evaluation into each category highlighted the fact that the well-formedness and verification queries are faster to evaluate than the other types, which is good news for the designers using `rbacUML`, as they are likely the two types of OCL queries they want to evaluate most often. Finally, ordered and selective evaluation strategies can be used separately or together to further decrease the worse-case evaluation time and reduce the amount of meaningless and/or uninteresting warnings and errors raised. Indeed, as one can see in Tables 5.2, 5.3 and 5.4, if some categories are not evaluated because the user has chosen not to evaluate them or because of the ordered evaluation strategy, the number of errors and warnings produced will be lower, and concentrated only on those categories that are of interest for the designer.

## 5.5. Fixing Performance

An analysis of the performance of the solution proposed in Chapter 4 for fixing incorrect models is done in this section. The evaluation is performed from three distinct angles:

the comparison of the constraint selection criteria, the comparison of the tree traversal strategies, and the assessment of the effect of the `NoChangeRbacDSML` profile. In its current state, the fixing algorithm does not scale very well. Indeed, for each node it creates, the entire model needs to be re-evaluated. Future work is discussed in the conclusion to improve the algorithm's efficiency. As a consequence, we have only evaluated it on relatively small models.

Four models are used to perform the evaluation.

The first one is the students' marks system that has been used in the previous chapters. To make it incorrect, the role hierarchy between the role `Professor` and the role `Student` has been removed, leading to the model represented in Figure 5.3. The model validation raises one error, a violation of the Granted constraint on the `Smith_Create Marks` element.

The second model is a larger model, created for the very purpose of this evaluation. It is made of 10 users, 3 roles, 15 permissions, 15 resources, 5 Granted scenarios and 5 Forbidden scenarios, for a total of 53 elements. It raises 6 errors: 5 on Granted scenarios, and 1 on a Forbidden scenario.

The third model is a modified version of the second one, with only one error, on a Forbidden scenario.

The fourth model is also a modified version of the second one, with one error on a Forbidden scenario, and one error on a Granted scenario.

To make sure that the algorithm eventually stops, a tree depth limit has been set to 20 for all models. It was necessary to have a tree depth at least as large as the number of errors on each model, to increase the chances of finding perfect solutions. Still, the evaluation sometimes takes a very, very long time, so two additional termination constraints were introduces: only the first five solutions are returned, and if they have not

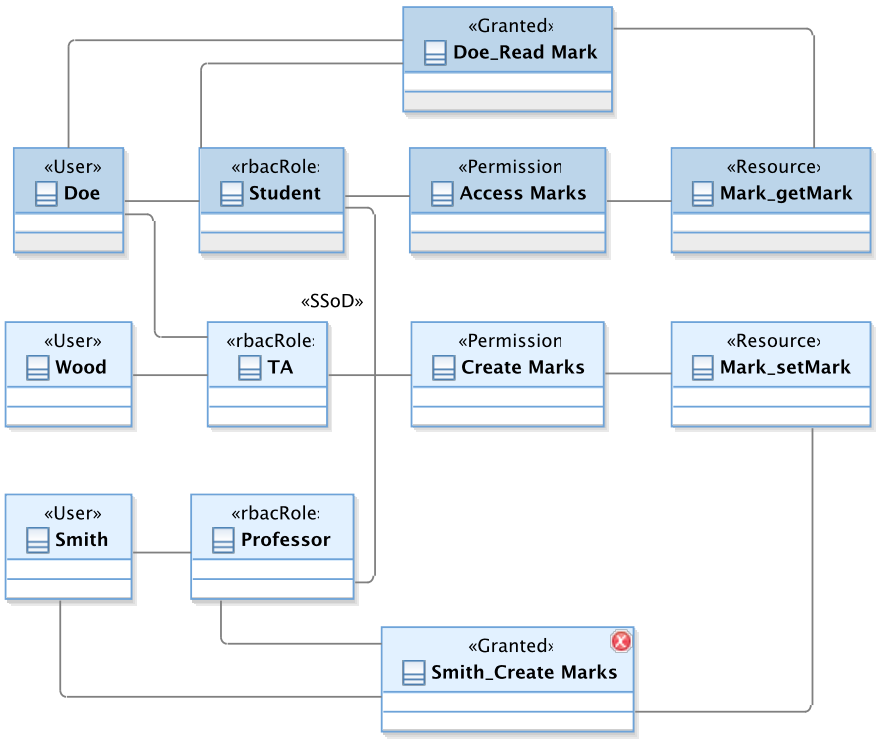



**Figure 5.3.:** Incorrect model for the student marks system used for evaluating the model fixing performance

been found within 30 minutes, the evaluation is stopped. Furthermore, each evaluation was carried out three times and the lowest values were selected, to account for differences caused by the OS process scheduler or other services and software running on the testing machine. The evaluation was carried out using the same machine as for the `rbacUML` evaluation performance study.

It has been argued in Chapter 4 that designers are likely to be more interested in solutions that are closer to the original model, i.e. solutions that minimise the changes made to the model. A function $scost(x)$ has been defined that computes the cost of a solution as the sum of the costs of each fix that constitute the solution: $scost(S) = \sum fcost(fix_i), \forall fix_i \in S$, where $S$ represents a solution, which is a list of fixes. The cost of a fix, as discussed in Chapter 4, can be computed in various ways depending on the designer's preference and the specificities of the DSML considered. For this study, it is important to try to be as precise as possible while still being general enough for the results to apply broadly. The following function is proposed with an aim to generate a cost that is simple to compute and relevant to `rbacDSML`: $fcost(F) = \sum ccost(c_1), \forall c_i \in F$, where $F$ is a fix, or a set of changes. The cost of changes is then defined as follows: $ccost(c) = 1$ if the change is the atomic addition or deletion of an association, and $ccost(c) = 2$ if the change is the atomic addition of a new element. In `rbacDSML`, elements are never deleted, so there is no need to define a cost for that operation.

The rationale behind the difference in cost between the addition/deletion of an association and the addition of an element stems from the very nature of `rbacDSML`: it is indeed reasonable to expect that, in an organisation, the creation of a new role or a new permission is a decision that is less likely to happen (the organisation's structure presumably changes less often than its members and their position in the structure), and that is taken much more seriously, than the addition or deletion of a particular assignment. Indeed, as roles are supposed to match the organisation's structure, the

addition of a new role would mean a modification of the company's structure, a decision unlikely to be made by a single designer in order to get rid of an annoying violation of an OCL constraint.

### 5.5.1. OCL Constraint Selection

#### Evaluation Criteria

In every node in the solution tree that has a model that violates several instances of the OCL constraints, a choice must be made over which instance of which constraint to fix. In Section 4.5.1 it is argued that an ordering of the selection of the next error to fix based on the categories of the OCL constraints will lead to fewer unnecessary branches to be considered.

The evaluation performed here compares three constraint selection strategies. The first one will evaluate the Granted constraints first, then Forbidden, roles activation, DSoD and finally SSoD. The second one is the opposite, i.e. SSoD first, followed by DSoD, roles activation, Forbidden, and finally Granted. The third one follows the categories order, i.e. the SSoD, DSoD and role activation constraints first (in no particular order), then Granted and Forbidden (in no particular order). When the name of the violated constraint is not enough to select an error to fix, the lexicographic order over the context's name is used.

#### Results

The results of the evaluation on model 2 are summarised on Table 5.5. Model 2 was chosen for its large number of errors, highlighting the importance of carefully selecting which error to fix first.

**Table 5.5.:** Comparison of constraint selection strategies (time in ms)

| Name | Granted first | | Granted last | | Categories | |
|---|---|---|---|---|---|---|
| | cost | time | cost | time | cost | time |
| Sol 1 | 6 | 312982 | 7 | 1346355 | 6 | 321610 |
| Sol 2 | 8 | 328293 | 7 | 1348707 | 8 | 337580 |
| Sol 3 | 7 | 331114 | 7 | 1358302 | 7 | 340628 |
| Sol 4 | 8 | 335359 | 7 | 1360655 | 8 | 345015 |
| Sol 5 | 8 | 343904 | 7 | 1370317 | 8 | 353800 |
| Total | - | 343998 | - | 1370394 | - | 353897 |

It appears immediately that the first and the last approaches return solutions of the same cost in about the same time, whilst the second approach returns different solutions, and takes much longer. The reason is fairly straightforward: fixing errors for constraints of types $I$ and $II$ generates more possible solutions than fixing errors for constraints of type $III$, because of the need to create lots of new paths, which is not necessary in type $III$. Therefore, the evaluation shows that the choice of the next error to fix should depend on the corresponding constraint's type, more than on the dependencies between constraints.

## 5.5.2. Traversal Strategies

### Evaluation Criteria

Since the traversal strategies described in Section 4.5.3 are similar to Harman and Jones' search-based software engineering [40], the evaluation of their performance is done following the methodology they propose.

Harman and Jones describe base line validity as follows:

**Definition 14.** *"To achieve a measure of base line acceptability a meta-heuristic technique must out-perform a purely random search. That is, meta-heuristics should find better solutions or find them with less computational effort than random search." [40, p.3]*

In the case of the traversal strategies for fixing models, the BFS traversal strategy is used as the random search that the meta-heuristics must outperform. Whilst not exactly random, it is the most naive approach, and any acceptable meta-heuristic must outperform it. The representation of a solution is a path from the root of the tree to a leaf that represents a correct model. The path gives a list of fixes that bring the root model to a correct state. The fitness function is the cost of a solution, and it needs to be minimised, i.e. solutions with a lower cost are better than solutions with a higher cost. The efficiency of each solution is also assessed, by calculating the time it takes to find 5 solutions that make the model correct.

### Results

**Table 5.6.:** Comparison of traversal strategies for the student marks system (time in ms)

| Name | BFS | | DFS | | Num. Errors | | Red. Errors | | Avg. Cost | | Combined Cost | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | cost | time | cost | time | cost | time | cost | time | cost | time | cost | time |
| $1^{st}$ Sol | 1 | 3112 | 1 | 4278 | 1 | 3982 | 1 | 3285 | 1 | 4087 | 1 | 3957 |
| $2^{nd}$ Sol | 1 | 4259 | 1 | 5453 | 1 | 5149 | 1 | 4376 | 1 | 5197 | 1 | 5101 |
| $3^{rd}$ Sol | 1 | 7523 | 1 | 8765 | 1 | 8329 | 1 | 7534 | 1 | 8282 | 1 | 8546 |
| $4^{th}$ Sol | 4 | 14410 | 10 | 13202 | 4 | 11362 | 10 | 11539 | 4 | 11188 | 4 | 11611 |
| $5^{th}$ Sol | 7 | 15340 | 10 | 15287 | 7 | 12322 | 10 | 13612 | 7 | 12133 | 7 | 12622 |
| Total | 14 | 15379 | 12 | 15393 | 10 | 12384 | 12 | 13708 | 10 | 12185 | 10 | 12668 |

The first model, the students marks system, has been evaluated using each of the traversal strategies from Chapter 4. The results of the evaluation are presented in Table 5.6. For each solution found, the cost and the time it took to find it are available. The total running time, as well as the number of nodes created in the tree, are available

at the bottom of the table. Each and every strategy managed to produce 5 solutions within about 15 seconds. In fact, looking at the total line at the bottom of the table, it comes immediately that all the strategies except DFS did complete faster than BFS, and they all did so using less nodes than BFS. This would be particularly important with larger models, as each node requires the evaluation of the model, which can be long.

Looking at individual solutions shows a more mixed picture: no strategy could beat BFS for the time to reach the first solution, but they catch up later. Moreover, both the DFS and the reduction of errors strategies did produce solutions that are less fit than BFS.

**Table 5.7.:** Comparison of traversal strategies for a large model (time in ms)

| Name | Num. Errors | | Avg. Cost | |
|---|---|---|---|---|
| | cost | time | cost | time |
| $1^{st}$ Sol | 12 | 311133 | 6 | 321610 |
| $2^{nd}$ Sol | 12 | 312498 | 8 | 337580 |
| $3^{rd}$ Sol | 12 | 313840 | 7 | 340628 |
| $4^{th}$ Sol | 12 | 315217 | 8 | 345015 |
| $5^{th}$ Sol | 12 | 316582 | 8 | 353800 |
| | nodes | time | nodes | time |
| Total | 234 | 316778 | 254 | 353897 |

The evaluation of the second model is summarised in Table 5.7. The table is smaller, because most of the strategies failed to produce 5 solutions in less than 30 minutes. In fact, the BFS strategy was left running for over 12 hours and still did not manage to produce 5 solutions. This, of course, highlights the need for carefully chosen strategies. The only two strategies to return solutions in under 30 minutes were the number of errors strategy and the average cost strategy. They returned solutions in less than 6 minutes.

As one can see from the table, the average cost strategy did find fitter solutions, but it took a bit longer, and used a few more nodes than the number of errors strategy, which was also faster at finding a first solution.

**Table 5.8.:** Comparison of traversal strategies for the third model (time in ms)

| Name | BFS | | DFS | | Num. Errors | | Red. Errors | | Avg. Cost | | Combined Cost | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | cost | time | cost | time | cost | time | cost | time | cost | time | cost | time |
| $1^{st}$ Sol | 1 | 7891 | 1 | 7884 | 1 | 8399 | 1 | 8222 | 1 | 7981 | 1 | 8059 |
| $2^{nd}$ Sol | 2 | 13597 | 2 | 13657 | 2 | 14457 | 2 | 14317 | 2 | 13668 | 2 | 13873 |
| $3^{rd}$ Sol | 2 | 16609 | 2 | 16388 | 2 | 17199 | 2 | 17137 | 2 | 16751 | 2 | 16658 |
| $4^{th}$ Sol | 2 | 19489 | 2 | 19170 | 2 | 19966 | 2 | 19912 | 2 | 19626 | 2 | 19313 |
| $5^{th}$ Sol | 3 | 23956 | 3 | 23356 | 3 | 24110 | 3 | 24059 | 3 | 24069 | 3 | 23413 |
| Total | 15 | 23996 | 15 | 23412 | 15 | 24146 | 15 | 24100 | 15 | 24111 | 15 | 23452 |

The evaluation of the third model is summarised in Table 5.8. It is very interesting to notice that all strategies perform almost the same. In fact, the differences between them are so small that they cannot be ranked. This is due to the fact that they did not have to be used at all, as at least five solutions were generated with just one fix.

**Table 5.9.:** Comparison of traversal strategies for the fourth model (time in ms)

| Name | BFS | | Num. Errors | | Red. Errors | | Avg. Cost | | Combined Cost | |
|---|---|---|---|---|---|---|---|---|---|---|
| | cost | time | cost | time | cost | time | cost | time | cost | time |
| $1^{st}$ Sol | 3 | 171210 | 3 | 150511 | 3 | 153819 | 2 | 272244 | 2 | 157088 |
| $2^{nd}$ Sol | 4 | 176641 | 4 | 155599 | 4 | 158778 | 4 | 292412 | 4 | 171545 |
| $3^{rd}$ Sol | 4 | 179404 | 4 | 158122 | 4 | 161296 | 3 | 296023 | 3 | 174161 |
| $4^{th}$ Sol | 4 | 182140 | 4 | 160693 | 4 | 163830 | 4 | 301794 | 4 | 178125 |
| $5^{th}$ Sol | 5 | 186437 | 5 | 164599 | 5 | 167715 | 4 | 313282 | 4 | 186124 |
| Total | 123 | 186491 | 123 | 164656 | 123 | 167812 | 134 | 313922 | 134 | 186161 |

The evaluation of the fourth model is summarised in Table 5.9. Compared to the previous model, one immediately notices that the strategies produce less similar results. Indeed, both the average cost and the combined cost strategies produce fitter solutions,

even though the other strategies all produce equally fit solutions. The time information is more interesting: indeed, the reduction of errors and number of errors perform better than BFS, while the combined cost strategy performs similarly to BFS, and average cost performs much worse. DFS did not terminate on time, hence it is not included in the table.

#### Summary

The comparison of the traversal strategies did not highlight one particular strategy as performing consistently better than the other ones, either in terms of time or in terms of the order in which solutions are found. These conflicting results seem to indicate that the choice of one strategy over another may depend on some properties of the incorrect model, such as the number of errors or their type, for example. The validation of this hypothesis would require a deeper evaluation, using larger models. This can only be done once the fixing algorithm's scalability has been addressed.

### 5.5.3. The `NoChangeRbacDSML` extension of the `rbacDSML` Profile

#### Evaluation Criteria

The last evaluation criteria in this section is the use of the `NoChangeRbacDSML` profile. The profile is described and discussed in Chapter 3, Section 4.5.2, and allows designers to make sure that any solution proposed will not delete some associations or add some element, according to the designer's annotations on a model.

Here the time it takes to generate 5 acceptable solutions is measured, according to three scenarios: the first one is a model without any `NoChangeRbacDSML` stereotype applied; the second one is a model where the policy, i.e. the assignment of permissions to

resources, cannot be modified; the third one is a model where the scenarios cannot be modified.

### Results

**Table 5.10.:** Effect of the `NoChangeRbacDSML` stereotype on the student marks system (time in ms)

| Solution | No `NoChangeRbacDSML` | | Policy | | Scenarios | |
|---|---|---|---|---|---|---|
| | cost | time | cost | time | cost | time |
| Sol 1 | 1 | 4087 | 1 | 3242 | 1 | 3111 |
| Sol 2 | 1 | 5197 | 1 | 6501 | 1 | 6453 |
| Sol 3 | 1 | 8282 | 4 | 9786 | - | - |
| Sol 4 | 4 | 11188 | 6 | 10807 | - | - |
| Sol 5 | 7 | 12133 | 7 | 16986 | - | - |
| | nodes | time | nodes | time | nodes | time |
| Total | 10 | 12185 | 15 | 17112 | 6 | 7815 |

The first model to be evaluated was the student marks system, as summarised in Table 5.10. One immediately notices that the third test, where scenarios cannot change, only produces two solutions, and finishes much faster than the other two tests. Indeed, all other solutions that exist involve at least one change to the associations attached to a scenario, and are therefore forbidden.

It is also worth noting that the second test, where the policy does not change, takes longer to generate solutions than the first test, which does not use the `NoChangeRbacDSML` profile. One could also claim that the second test's solutions are less fit than the first test's, but one must keep in mind that, in the second test, the designer has specifically indicated that he is not interested in certain solutions. Therefore, he gets 5 potentially interesting solutions, instead of having to discard a number of them immediately after test 1, since they do not conform to his requirements.

**Table 5.11.:** Effect of the `NoChangeRbacDSML` stereotype on a large model (time in ms)

| Solution | No `NoChangeRbacDSML` | | Policy | | Scenarios | |
|---|---|---|---|---|---|---|
| | cost | time | cost | time | cost | time |
| Sol 1 | 6 | 321610 | 6 | 151998 | 9 | 220370 |
| Sol 2 | 8 | 337580 | 8 | 166106 | 9 | 221806 |
| Sol 3 | 7 | 340628 | 7 | 168698 | 9 | 230340 |
| Sol 4 | 8 | 345015 | 8 | 172641 | 9 | 231738 |
| Sol 5 | 8 | 353800 | 8 | 180460 | 9 | 237307 |
| | nodes | time | nodes | time | nodes | time |
| Total | 254 | 353897 | 135 | 180563 | 170 | 237430 |

The evaluation of the second model is shown in Table 5.11. In this case, each test produced five solutions. One will notice, however, that the second and the third test, both of which use the `NoChangeRbacDSML` profile, took significantly less time to complete than the "vanilla" test, and used much fewer nodes. This is due to the fact that branches that involve a modification forbidden by the `NoChangeRbacDSML` annotations are not explored, making the discovery of the other, acceptable solutions much faster.

### 5.5.4. Discussion

The three criteria used in the above evaluation show some promising results and highlight some interesting differences between the several approaches used. The comparison of the error selection strategies shows that choosing the best strategy, i.e. the one that keeps the tree as narrow as possible, especially in the beginning, avoids the multiplication of nodes and the increase in solution generation time.

The comparison of the traversal strategies highlights the differences between several strategies, and the need to balance a search for the best solutions with time efficiency.

The study of the `NoChangeRbacDSML` profile then shows that using the profile not only ignores useless results for the designer, but may also dramatically speed up the solution discovery time.

Perhaps the biggest weakness of this evaluation is the small number of models considered. However, even with this small number of models, the evaluation has shown that a solution adapted for one model might not be adapted for another, hence it is probably impossible to draw conclusions that would apply to all `rbacDSML` models, let alone all models of any DSML, even with a large number of models considered. The evaluation indicates that expert knowledge will be required to select the most appropriate settings for a particular model, if one needs solutions to be generated relatively quickly. The evaluation has also shown that the more errors there are on a model, the longer the generation of solutions takes. Hence, one would recommend that designers evaluate their models frequently, in order to take remedial actions as soon as possible. This further stresses the need for improvements in the evaluation speed.

Finally, it is worth pointing out that the plug-in was by no means optimised, and should indeed be treated as an early product rather than a stable and optimised solution. The generation time, especially on large models with lots of errors, would greatly benefit from optimisations that reduce the number of nodes to consider, and from optimisation that reduce the evaluation time of models. Egyed's approach for incremental evaluation of models [28] could possibly bring massive time savings here.

## 5.6. A Real-Life Case Study

We illustrate the utility of `rbacUML` with a real example, the cloud-based repository hosting service `chiselapp.com`. `ChiselApp` is a server-side PHP program that allows software developers to host and share projects using the `Fossil` distributed version

control system. There are two layers of access controls: at the account layer, the PHP program manages the authentication of developers through a set of roles for the website; at the repository layer, the built-in web subsystem of `Fossil` manages the access to the repositories through a database table inside the `Fossil` repository.

The account-managed repositories are classified into private and public. The public repositories are openly accessible to any visitor of the website. The private repositories are only exposed to the account owners. Without logging into `chiselapp.com`, even the owner cannot access these private repositories. Because the `Fossil` repositories are distributed, once granted access by the owner, the repository-level access control allows additional guests, committers or administrators to pull, sync, edit or even delete the repository.

In order to verify the RBAC properties of a system that does not provide its design in UML, we applied the reverse engineering toolkit `PHP_UML` [1] to recover the deployment view of the system from the source code (Figure 5.4). Notice that PHP programs are not purely object-oriented, some of the high-level functions in the `.php` artefacts are not necessarily encapsulated by PHP classes. Therefore, pseudo UML classes with a single operation are created to represent those functions. The recovered XMI model provides the traceability links between the low-level PHP classes and the high-level `.php` artefacts, which are not shown here for clarity.

According to the implementation, we modelled the access control configuration as shown in Figure 5.5. In this diagram, we identify three typical users Alice, Bob, and Charles and associate them with representative roles such as *Account Guest*, *Account Owner*, *Site Admin* for the account management, and *Repository Guest*, *Repository Committer*, and *Repository Owner* for the repository management. The relations between these roles indicate the inheritance of permissions from the parent roles.

[1] http://pear.php.net/package/PHP_UML

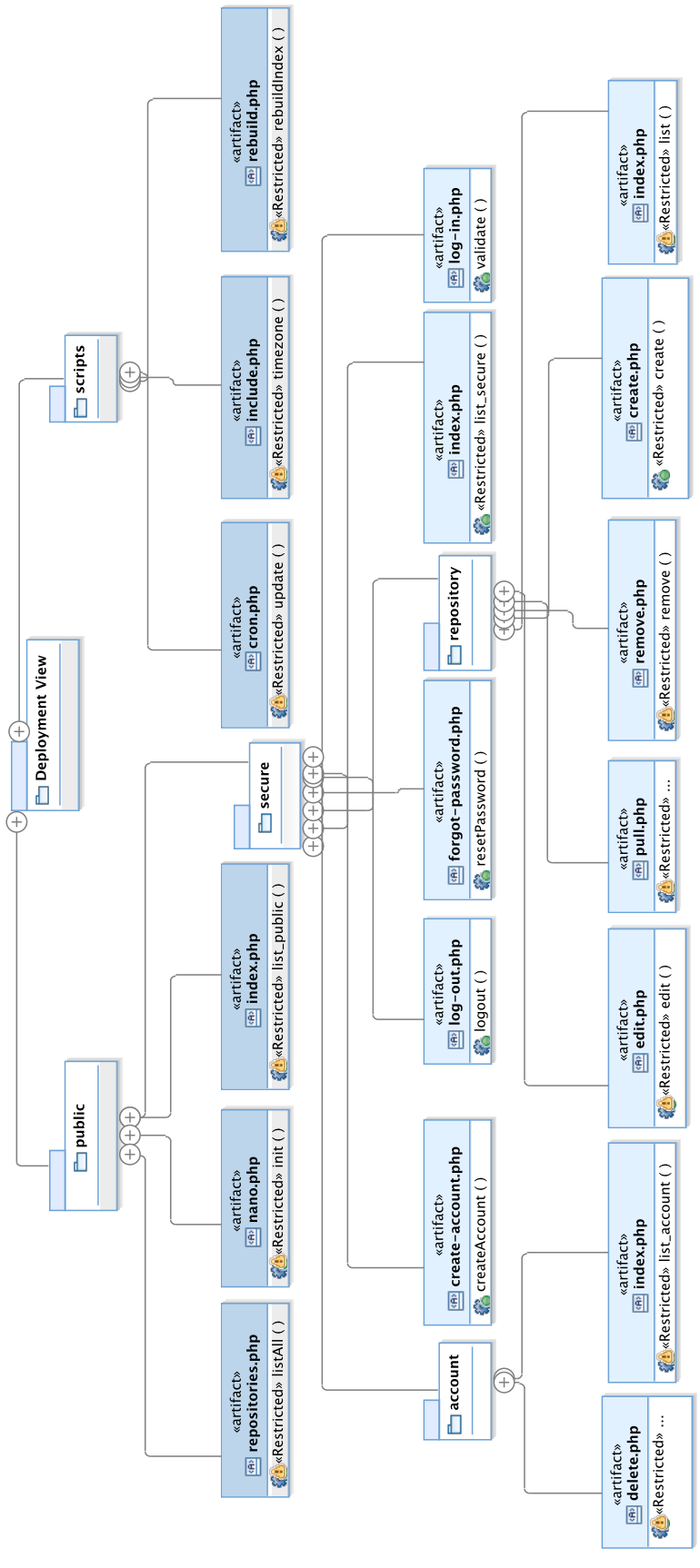



**Figure 5.4.:** The partial class diagram recovered from the source code of `ChiselApp`

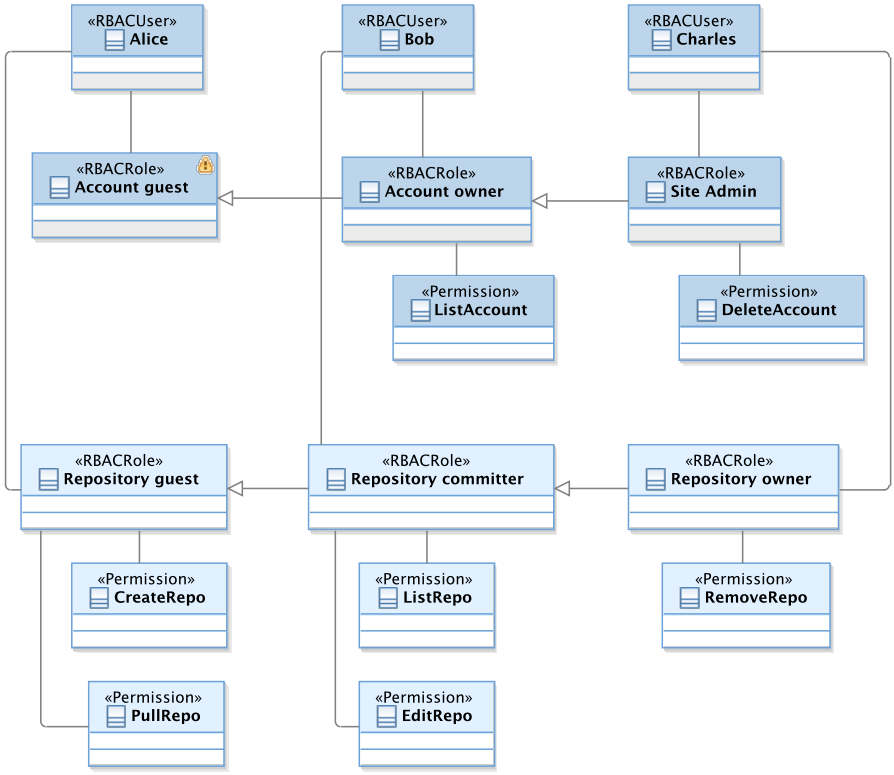



**Figure 5.5.:** Concepts of users, roles, and permissions are instantiated as an access control class diagram.

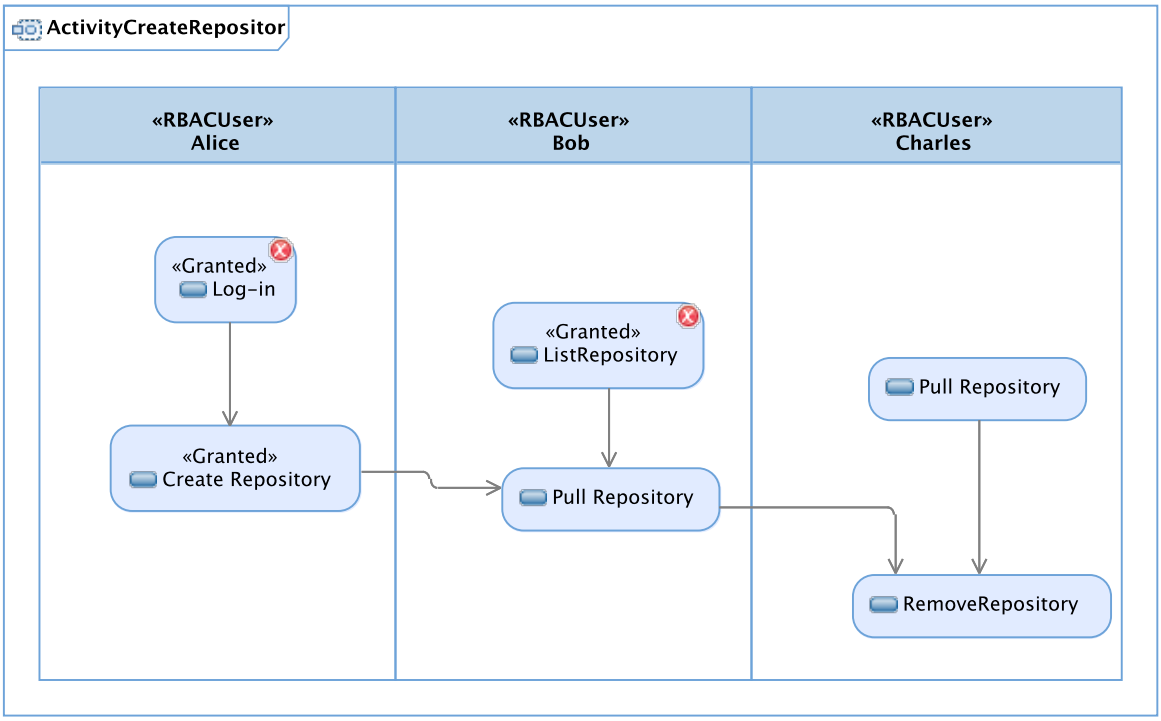



**Figure 5.6.:** The activity diagram shows two actions that violate OCL constraints

After modelling the RBAC concepts, we added stereotypes to those operations in the class diagram (Figure 5.4) that require a permission as a precondition in the code, e.g. the `edit()` operation of the `edit.php` artefact class is restricted by the `EditRepo` permission (see Figure 5.5). To illustrate the business logic, Alice creates a repository that is subsequently listed and pulled by Bob and Charles, until sometime later Charles removes it (Figure 5.6). After the modelling exercise, we obtained 32 classes, 85 operations (67 of them in the low-level classes not shown in Figure 5.4) and 6 actions (Figure 5.6) in the business logic, and 3 users, 6 roles and 7 permissions in the access control configuration (Figure 5.5).

With RSA, we validated the RBAC constraints using the `rbacUML` plug-in, and found 2 errors in the `ChiselApp` model. Figure 5.6 shows the red marks that indicate where the errors were found.

First, the *Login* action was marked as restricted by the permission of *ListRepo*. However, the PHP implementation never checks such a permission. It was our misunderstanding as modellers when creating the activity diagram that the login needs to be protected. Indeed, every user of `ChiselApp` is allowed to login by the business logic of the PHP program. Therefore, `rbacUML` found an error in the manually annotated model that wrongly represents the implementation in the code.

Second, *Bob* was not allowed to edit the repository, even though he has been assigned as the owner of the repository. This is a more remarkable error. In the access control configuration diagram, Bob has the role *Repository Committer* with the permission *EditRepos*. In the Activity diagram corresponding to the program execution at runtime, however, this role was not activated. Therefore, it is important to check whether Bob is the committer to allow him to edit the repository. The implementation of `ChiselApp` delegates such a check to the `Fossil` toolkit. However, one can construct a test scenario whereby Bob is the *AccountOwner* but not a *RepositoryCommitter*. Using this test case, we have demonstrated that `ChiselApp` should not delegate the verification to the other tool, otherwise there is an inconsistency in the access control configuration. In other words, this is confirmed as a bug in the original implementation of `ChiselApp`. The bug had already been reported on the `ChiselApp` issue tracking system, but the maintainer argued that the bug is, in fact, a feature. We disagree with the maintainer's opinion, because the default settings for new users violate the access control property we verified.

In brief, modelling the access control properties of a real-life cloud-based repository hosting service showed that `rbacUML` can be useful to fix design issues even after the implementation has been done. It requires some reverse engineering effort, but the cost is justified if security errors are found.

### 5.6.1. Lessons Learned

The `ChiselApp` case study was our first try at using `rbacUML` on a real application. We learned valuable lessons during the process, and were able to identify a few aspects of `rbacUML` that could be improved.

Recovering the class diagram for `ChiselApp` was very easy, thanks to `PHP_UML`. Recovering the activity diagram was however more complex, as it required manual inspection of the code. It may be a good idea to investigate how to automate the process, at least partially.

Another issue that we encountered has to do with UML itself: as soon as a UML model grows to a realistic size, it becomes very difficult to navigate in its diagram form. The tree form provided by RSA's model explorer often proved a more practical solution. We think that the ability to select at runtime which elements to include in a diagram may help the navigation of large models.

On the positive side, once we had found the issue, the graphical representation makes it very easy to visualise. The ability to tweak the model and re-verify it after making a few changes was also very useful to explore the possible ways to solve the error.

# Chapter 6.

# Conclusions

In this dissertation, we have proposed a new Model-Driven Engineering approach for modelling, analysing and fixing RBAC concerns by extending UML models. The proposed approach comprises a DSML as well as a DSMAL, allowing stakeholders to select the most appropriate language for the specific activities they want to perform. The contributions build and improve on existing approaches on several points.

**Our approach is general** because it has been designed using the standard UML extension mechanisms: stereotypes, associations and OCL queries. This allows designers, on the one hand, to adopt the approach with having to learn new languages, tools or methodologies, if they are already familiar with UML; and on the other hand to port our approach to other UML tools if necessary. While our approach was implemented as plug-ins for IBM Rational Software Architect, we have provided all the necessary information to port it to any other modelling tool that supports the UML standard, its extension mechanism, and OCL queries evaluation.

**Our approach is systematic** because it is centred on two UML profiles that define a Domain-Specific Modelling Annotations Language (DSMAL) as well as a Domain-Specific Modelling Language (DSML), which have been developed following Selic's guidelines for systematic DSML development [95].

**Our approach does not require stakeholders to write code or queries** themselves because the queries have already been defined as part of the two profiles. However, should they want to expand the profiles' capabilities or even run model-level queries, they have the possibility to do so.

**The `rbacUML` provides a general categorisation of OCL queries** to better understand the different types of analyses that can be run on models created using DSMALs or DSMLs.

**Strategies for reducing the analysis time** were developed on the basis of a proposed categorisation of OCL queries and the dependencies identified between them. An evaluation of those strategies has found them to be effective.

**An integration with organisational repositories is considered** through the `LDIF` import filter from existing user directories.

**rbacDSML models can be automatically fixed** when one or several errors are detected. The set of generated solutions is both correct and, under some assumptions, complete.

## 6.1. Future Work

The work presented in this dissertation can be extended in several area, as discussed below, to improve designers' experience when dealing with domain-specific concerns, and access control in particular.

### 6.1.1. Transformations

Both representations are derived from the same domain meta-model. Since the choice of profile to use depends on the circumstances, designers need transformations from one profile to the other, and back. It must be possible to reflect changes made to one representation on the other one, in order to keep both models synchronised. Since changes could happen in both representations, it is important to define a bidirectional transformation that would allow designers to transform a DSMAL model into a DSML, and back. Since the DSML contains a subset of the information contained in the DSMAL, tools such as GRoundTram [41] allow one to define a transformation from the DSMAL to the DSML, and the transformation from the DSML back to the DSMAL comes "for free". If both models can change before being synchronised, then the problem is similar

to model-code synchronisation problems that MDE approaches face [114]. A similar approach to what is needed in this case is Guerra and de Lara's use of triple graph transformations to derive views from models [38]. However, their views are not editable.

### The Problem with DSMALs

The transformations called for in this dissertation differ from transformations between "ad-hoc" DSMLs and DSMLs implemented as UML profiles, such as those described by Wimmer [113]. The latter are produced semi-automatically. Wimmer assumes that a transformation can "destroy" the target model and entirely replace it with the newly generated model. This is a fair assumption when dealing with DSMLs only, as there is no more information in one representation than in the other. But in the case of a DSMAL, such an approach will destroy all the information in the model that is not related to the DSML. In the example in Chapter 3, a destructive approach would completely erase the `Student`, `Module`, `Professor` and `TA` classes, as well as the `Mark::getDate()` and `Mark::setDate()` operations, in the class diagram (Chapter 3, Figure 3.7a) alone. This problem would not occur with bidirectional transformations defined with GRoundTram, as it keeps track of the information that was removed during the forward transformation between the DSMAL and the DSML.

Yet, Wimmer's approach can still partially apply here, especially his discussion of the mapping between both languages. Since both languages stem from the same domain meta-model, it is likely that many concepts will have a one-to-one mapping. However, the necessary redundancy in the DSMAL means that some mappings will be one-to-many, which further complicates the creation of the transformation.

### Multiple Profiles

Annotating UML models with concepts from one domain is already challenging, but what if one wants to annotate it with concepts from *several* domains? There may be many interesting ways of using DSMLs to model some aspects of the software: RBAC is one of them, but there are others, such as performance, specific business rules, persistence, etc. It would make sense to have a DSML as well as a DSMAL for each of them. The same general-purpose model could then be annotated with stereotypes from several profiles, which brings new challenges to keep the general-purpose model and the DSMLs in sync, and to prevent conflicts from happening.

If the same general-purpose model is annotated with concepts from several profiles, there is a chance that synchronisation problems will occur. Indeed, if a model is annotated with both access control and performance annotations, and changes are done concurrently to their respective DSML views, then the transformation that reflects these changes back to the general-purpose model will be more difficult. This problem is similar to the model-code synchronisation problem typically encountered in MDE [114].

It is possible that two DSMALs will bring conflicting annotations, and therefore a mechanism will be necessary to detect them. For example, let's assume two DSMALs, one for performance and one for persistence. If a particular element is marked with a performance requirement, and then marked with a persistence stereotype that involves saving the element's state in a database, the persistence will have a negative effect on the performance. These potential conflicts between stereotypes will have to be identified on a case by case basis. OCL constraints could be used to detect potential conflict and bring them to the designer's attention.

Mussbacher et al's work [69] addresses this problem of detecting interactions between different aspects. Their approach captures aspects as UML sequence diagrams and Aspect-

oriented Use Case Maps (AoUCM). Domain-specific annotations as well as influence models are then used to automatically analyse how different aspects influence each other. Several case studies have already been considered, but it would be very interesting to study how their approach applies to `rbacUML` and `rbacDSML`.

### 6.1.2. Translating OCL Constraints

In Chapter 3, we have defined OCL constraints for both `rbacUML` and `rbacDSML`. Since the same domain-level properties need to be guaranteed, it is reasonable to expect that one could create their OCL constraints on the DSML, which is the simplest model and therefore requires relatively simple constraints, and have them translated to be used with the DSMAL. After all, there is already a mapping between the concepts in the DSML and the concepts in the DSMAL.

However, the redundancy and the division of one concept into several ones will make this process more difficult. Not only is it necessary to create *new* OCL constraints to ensure consistency between redundant and spread out concepts, but the existing constraints may also have to take those into account, which would make them even more complex. An automated conversion process that would, given both profiles, the mapping of concepts from one to the other, and the OCL constraints for the DSML, produce the OCL constraints for the DSMAL, would be incredibly useful, as it would save time and reduce the occurrence of errors from the manual translation process. With GRoundTram, one could do this automatic conversion by giving a *filter- promotion* transformation for the transformation language UnQL+ [42]. Let $T$ be the mapping from DSMAL to DSML in UnQL+ and $C$ be a constraint on DSML. The filter promotion transformation is to transform *filter* $C \circ T$ to $T \circ$ *filter* $C'$ to promote the condition $C$ on the output of $T$ to a new condition $C'$ on the input.

In `rbacUML`, there is a one-to-one mapping for most concepts, which is relatively obvious from the two extensions of the UML meta-model. Three concepts, however, require a one-to-many mapping: the user, represented in the DSMAL by one class in the access control diagram and by any number of partitions in activity diagrams; the resources, represented in the DSMAL by an operation in a class diagram, and by any number of messages in a sequence diagram; the role activation, spread in the DSMAL as «`ActivateRoles`» and «`DeactivateRoles`» on scenarios, and over partitions.

This makes translating the OCL constraints from the DSML to the DSMAL quite difficult. For example, the split of the user concept into several elements means that a new constraint must be introduced to make sure that all user annotations that are supposed to represent the same user are consistent, i.e. they must have the same name. This also makes the OCL constraint that checks that roles activated by a user are also assigned to him more complicated. In the DSML, the constraint looks like:

```
context rbacDSML::Scenario inv:
self.user.rbacRole
->includesAll(self.rbacRole)
```

but in the DSMAL, it looks like:

```
context rbacUML::Granted inv:
self.base_Action.inPartition
.extension_RBACUser.aliasUser.rBACRole
->includesAll(self.rBACRole)
```

Because of the separation of the user in two concepts, another OCL constraint is also necessary to ensure well-formedness:

```
context rbacUML::User inv:
(self.base_Partition <> null)
implies (self.name = self.user.name)
```

### 6.1.3. Support for other Access Control Models

In this dissertation, the proposed access control approach is limited to RBAC. As shown in Chapter 2, it made sense because numerous access control models are built on top of RBAC, such as OrBAC or GEO-RBAC. Even ABAC is a superset of RBAC. Each of these access control models brings new challenges that may be addressed by extending the `rbacUML` and `rbacDSML` profiles. In particular, ABAC models will make profile design as well as modelling much more challenging, if one wants to keep true to our commitment to provide an *easy to use* approach: the fact that any attribute could be used will make it difficult, if not impossible, to manually write meta-model-level OCL constraints that work for all models. Alternative solutions will probably have to be explored in order to allow users to model ABAC concepts without writing any code or queries.

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# Appendix A.

# `rbacDSML` OCL Constraints

This section contains the OCL constraints for rbacDSML, as implemented in the tool. For a discussion of the differences between the constraints in the tool and the constraints as described in Chapter 3, see Chapter 5.

# A.1. Well-Formedness

## A.1.1. Activated roles must be assigned to the user

Finds roles that are activated by a scenario without having been assigned to the corresponding user.

```
context rbacDSML::Scenario inv:

self.getAllAttributes().opposite.owner
        ->select(user | user.getAppliedStereotype('rbacDSML::User') <> null).oclAsType(
            Class)
         .getAllAttributes().opposite.owner
        ->select(role | role.getAppliedStereotype('rbacDSML::rbacRole') <> null)
        ->union(self.getAllAttributes().opposite.owner
        ->select(user | user.getAppliedStereotype('rbacDSML::User') <> null).oclAsType(
            Class)
         .getAllAttributes().opposite.owner
        ->select(role | role.getAppliedStereotype('rbacDSML::rbacRole') <> null).
            oclAsType(Class).allParents())
->includesAll(self.getAllAttributes().opposite.owner
->select(role2 | role2.getAppliedStereotype('rbacDSML::rbacRole') <> null))
```

### A.1.2. SSoD

Finds role assignments that violate SSoD constraints.

```
context rbacDSML::User inv:

self.getAllAttributes().type.oclAsType(Class)->union(self.getAllAttributes().type.
    oclAsType(Class).allParents().oclAsType(Class))->select(elt | elt.oclAsType(Class).
    getAppliedStereotype('rbacDSML::rbacRole') <> null).oclAsType(Class)
->exists(role1, role2 | role1.oclAsType(Class).getAllAttributes()->select(prop | prop.
    oclAsType(Property).association.getAppliedStereotype('rbacDSML::SSoD') <> null).
    type.oclAsType(Class)
->includes(role2.oclAsType(Class))) = false
```

### A.1.3. DSoD

Finds role activations that violate DSoD constraints.

```
context rbacDSML::Scenario inv:

self.getAllAttributes().opposite.owner->select(role | role.getAppliedStereotype('
    rbacDSML::rbacRole') <> null)
->exists(role1, role2 | role1.oclAsType(Class).getAllAttributes()
        ->select(dsod | dsod.oclAsType(Property).association.getAppliedStereotype('
            rbacDSML::DSoD') <> null).opposite.owner->includes(role2)) = false
```

# A.2. Verification

## A.2.1. VER Granted

Finds «Granted» scenarios that the model does not conform to.

```
context rbacDSML::Granted inv:

self.getAllAttributes().opposite.owner
        ->select(role | role.getAppliedStereotype('rbacDSML::rbacRole') <> null).
            oclAsType(Class)
        ->union(self.getAllAttributes().opposite.owner->select(role | role.
            getAppliedStereotype('rbacDSML::rbacRole') <> null).oclAsType(Class).
            allParents().oclAsType(Class)).oclAsType(Class).getAllAttributes().opposite
            .owner
        ->select(permission | permission.getAppliedStereotype('rbacDSML::Permission')
            <> null)
->includesAll(self.getAllAttributes().opposite.owner
                                                    ->select(resource | resource.
                                                        getAppliedStereotype('
                                                        rbacDSML::Resource') <>
                                                        null).oclAsType(Class).
                                                        getAllAttributes().opposite
                                                        .owner
                                                    ->select(permission |
                                                        permission.
                                                        getAppliedStereotype('
                                                        rbacDSML::Permission') <>
                                                        null))
```

## A.2.2. VER Forbidden

Finds «Forbidden» scenarios that the model does not conform to.

```
context rbacDSML::Forbidden inv:

self.getAllAttributes().opposite.owner
        ->select(role | role.getAppliedStereotype('rbacDSML::rbacRole') <> null).
            oclAsType(Class)
        ->union(self.getAllAttributes().opposite.owner->select(role | role.
            getAppliedStereotype('rbacDSML::rbacRole') <> null).oclAsType(Class).
            allParents().oclAsType(Class)).oclAsType(Class).getAllAttributes().opposite
            .owner
        ->select(permission | permission.getAppliedStereotype('rbacDSML::Permission')
            <> null)
->includesAll(self.getAllAttributes().opposite.owner
                                                    ->select(resource | resource.
                                                        getAppliedStereotype('
                                                        rbacDSML::Resource') <>
                                                        null).oclAsType(Class).
                                                        getAllAttributes().opposite
                                                        .owner
                                                    ->select(permission |
                                                        permission.
                                                        getAppliedStereotype('
                                                        rbacDSML::Permission') <>
                                                        null))
= false
```

# Appendix B.

# `rbacUML` OCL Constraints

In this section, we provide a complete list of all the OCL queries in rbacUML, organised in categories. For a discussion of the categories, refer to Section 3.5.

# B.1. Well-formedness

## B.1.1. WF Activated roles cannot have been activated in the user partition

In an action stereotyped with «ActivateRoles», any role activated through the stereotype cannot also be activated through the «RBACUser» stereotype on the activity partition in which the action lies.

```
context rbacUML::ActivateRoles inv:
self.base_Action.inPartition.extension_RBACUser.rBACRole->intersection(self.rBACRole)->
    isEmpty()
```

## B.1.2. WF Activated roles must be assigned to the user

In an action stereotyped with «ActivateRoles», any role activated through the stereotype must also be assigned to the user corresponding to the activity partition in which the action lies.

```
context rbacUML::ActivateRoles inv:
self.base_Action.inPartition.extension_RBACUser.aliasUser.rBACRole
        ->union(self.base_Action.inPartition.extension_RBACUser.aliasUser.rBACRole.
            base_Class.allParents().oclAsType(Class).extension_RBACRole)
->includesAll(self.rBACRole)
```

### B.1.3. WF ActivateRoles must be applied to an action inside a user partition

The stereotype «ActivateRoles» can only be applied to an action that lies in an activity partition stereotyped with «RBACUser».

```
context rbacUML::ActivateRoles inv:
self.base_Action.inPartition.getAppliedStereotype('rbacUML::RBACUser') <> null
```

### B.1.4. WF ActivateRoles can only be applied on a Granted or a Forbidden action

The stereotype «ActivateRoles» can only be applied to an action stereotyped with either «Granted» or «Forbidden».

```
context rbacUML::ActivateRoles inv:
(self.base_Action.getAppliedStereotype('rbacUML::Granted') <> null)
or (self.base_Action.getAppliedStereotype('rbacUML::Forbidden') <> null)
```

### B.1.5. WF At least one role must be activated from ActivateRoles

If the «ActivateRoles» stereotype is applied on an action, then at least one role must be activated using the «ActivateRoles» stereotype.

```
context rbacUML::ActivateRoles inv:
self.rBACRole->size() > 0
```

### B.1.6. WF ActivateRoles cannot violate DSoD constraints

If roles are activated through the «ActivateRoles» stereotype, then the union of these roles with the set of roles activated in the user partition, minus the set of roles deactivated through the «DeactivateRoles» stereotypes if it is applied, cannot contain two roles that have a DSoD constraint between them.

```
context rbacUML::ActivateRoles inv:
(self.rBACRole
        ->union(self.base_Action.inPartition.extension_RBACUser.rBACRole)->asSet()
                ->symmetricDifference(if (self.base_Action.extension_DeactivateRoles =
                    null) then Set{} else self.base_Action.extension_DeactivateRoles.
                    rBACRole endif))
->forAll(role1, role2 | role1.dsod1->excludes(role2))
```

### B.1.7. WF At least one role must be deactivated from DeactivateRoles

If the «DeactivateRoles» stereotype is applied on an action, then at least one role must be deactivated using the «DeactivateRoles» stereotype.

```
context rbacUML::DeactivateRoles inv:
self.rBACRole->size() > 0
```

### B.1.8. WF Deactivated roles must be assigned to the user

In an action stereotyped with «DeactivateRoles», any role deactivated through the stereotype must also be assigned to the user corresponding to the activity partition in which the action lies.

```
context rbacUML::DeactivateRoles inv:
self.base_Action.inPartition.extension_RBACUser.aliasUser.rBACRole
        ->union(self.base_Action.inPartition.extension_RBACUser.aliasUser.rBACRole.
            base_Class.allParents().oclAsType(Class).extension_RBACRole)
->includesAll(self.rBACRole)
```

### B.1.9. WF Deactivated roles must have been actived in the user partition

In an action stereotyped with «DeactivateRoles», any role deactivated through the stereotype has been activated through the «RBACUser» stereotype on the activity partition in which the action lies.

```
context rbacUML::DeactivateRoles inv:
self.base_Action.inPartition.extension_RBACUser.rBACRole
        ->includesAll(self.rBACRole)
```

### B.1.10. WF DeactivateRoles must be applied to an action inside a user partition

The stereotype «DeactivateRoles» can only be applied to an action that lies in an activity partition stereotyped with «RBACUser»

```
context rbacUML::DeactivateRoles inv:
self.base_Action.inPartition.getAppliedStereotype('rbacUML::RBACUser') <> null
```

### B.1.11. WF DeactivateRoles can only be applied on a Granted or a Forbidden action

The stereotype «DeactivateRoles» can only be applied to an action stereotyped with either «Granted» or «Forbidden».

```
context rbacUML::DeactivateRoles inv:
(self.base_Action.getAppliedStereotype('rbacUML::Granted') <> null)
or (self.base_Action.getAppliedStereotype('rbacUML::Forbidden') <> null)
```

### B.1.12. WF Forbidden action must be inside a user partition

Actions stereotyped with «Forbidden» must lie in an activity partition stereotyped with «RBACUser».

```
context rbacUML::Forbidden inv:
self.base_Action.inPartition.getAppliedStereotype('rbacUML::RBACUser') <> null
```

### B.1.13. WF Forbidden action must have at least one Restricted operation

Actions stereotyped with «Forbidden» must have associations to at least one operation stereotyped with «Restricted».

```
context rbacUML::Forbidden inv:
self.operation->exists(op | op.getAppliedStereotype('rbacUML::Restricted') <> null)
```

### B.1.14. WF The same role cannot be both activated and deactivated on the same Forbidden action

In an action stereotyped with «Forbidden», the same role can't be both activated with «ActivateRoles» and deactivated with «DeactivateRoles».

```
context rbacUML::Forbidden inv:
((self.getAppliedStereotype('rbacUML::ActivateRoles') <> null)
and (self.getAppliedStereotype('rbacUML::DeactivateRoles') <> null))
        implies self.base_Action.extension_ActivateRoles.rBACRole
                ->intersection(self.base_Action.extension_DeactivateRoles.rBACRole)
                        ->isEmpty()
```

### B.1.15. WF the interaction must refer to exactly all the operations, no more, no less

If an interaction is associated to an action stereotyped with «Forbidden», the set of messages in the interaction must be the same as the set of operations in the action.

```
context rbacUML::Forbidden inv:
self.interaction <> null implies
self.interaction.allOwnedElements()
        ->select(elt | elt.oclIsTypeOf(Message)).oclAsType(Message)
        ->select(msg | msg.getAppliedStereotype('rbacUML::Restricted') <> null).
            signature->asSet()
= (self.operation)
```

### B.1.16. WF Granted action must be inside a user partition

Actions stereotyped with «Granted» must lie in an activity partition stereotyped with «RBACUser».

```
context rbacUML::Granted inv:
self.base_Action.inPartition.extension_RBACUser <> null
```

### B.1.17. WF Action cannot be stereotyped with both Granted and Forbidden

An action can't be stereotyped with both «Granted» and «Forbidden».

```
context rbacUML::Granted inv:
self.base_Action.getAppliedStereotype('rbacUML::Forbidden') = null
```

### B.1.18. WF Forbidden action must have at least one Restricted operation

Actions stereotyped with «Granted» must have associations to at least one operation stereotyped with «Restricted».

```
context rbacUML::Granted inv:
self.operation->exists(op | op.getAppliedStereotype('rbacUML::Restricted') <> null)
```

### B.1.19. WF The same role cannot be both activated and deactivated on the same Granted action

In an action stereotyped with «Granted», the same role can't be both activated with «ActivateRoles» and deactivated with «DeactivateRoles».

```
context rbacUML::Granted inv:
((self.getAppliedStereotype('rbacUML::ActivateRoles') <> null)
and (self.getAppliedStereotype('rbacUML::DeactivateRoles') <> null))
        implies self.base_Action.extension_ActivateRoles.rBACRole
                ->intersection(self.base_Action.extension_DeactivateRoles.rBACRole)->
                    isEmpty()
```

### B.1.20. WF the interaction must refer to exactly all the operations, no more, no less

If an interaction is associated to an action stereotyped with «Granted», the set of messages in the interaction must be the same as the set of operations in the action.

```
context rbacUML::Granted inv:
self.interaction <> null implies
self.interaction.allOwnedElements()
        ->select(elt | elt.oclIsTypeOf(Message)).oclAsType(Message)
        ->select(msg | msg.getAppliedStereotype('rbacUML::Restricted') <> null).
            signature->asSet()
= (self.operation)
```

### B.1.21. WF A class can only be stereotyped with one of RBACUser, RBACRole or Permission

A class cannot have more than one of the «RBACUser», «RBACRole» and «Permission» stereotypes.

```
context rbacUML::Permission inv:
self.getAppliedStereotype('rbacUML::RBACUser') = null
and
self.getAppliedStereotype('rbacUML::RBACRole') = null
```

### B.1.22. WF A class can only be stereotyped with one of RBACUser, RBACRole or Permission (2)

A class cannot have more than one of the «RBACUser», «RBACRole» and «Permission» stereotypes.

```
context rbacUML::RBACRole inv:
self.getAppliedStereotype('rbacUML::RBACUser') = null
and
self.getAppliedStereotype('rbacUML::Permission') = null
```

### B.1.23. WF A class can only be stereotyped with one of RBACUser, RBACRole or Permission (3)

A class cannot have more than one of the «RBACUser», «RBACRole» and «Permission» stereotypes.

```
context rbacUML::RBACUser inv:
self.getAppliedStereotype('rbacUML::RBACRole') = null
and
self.getAppliedStereotype('rbacUML::Permission') = null
```

### B.1.24. WF A user cannot be assigned two roles if there is an SSoD constraint between them

If there is an SSoD constraint between two roles, they cannot be both assigned to a user

```
context rbacUML::RBACUser inv:
self.rBACRole
        ->union(self.rBACRole.base_Class->asSet().allParents().oclAsType(Class).
            extension_RBACRole)->asSet()
->forAll(rle1, rle2 | rle1.ssod1->includes(rle2) = false)
```

### B.1.25. WF RBACUser applied on a user partition must have exactly one alias

If the stereotype «RBACUser» is applied on an activity partition, it must have exactly one *alias* association.

```
context rbacUML::RBACUser inv:
(self.base_ActivityPartition <> null)
        implies (self.aliasUser->size() = 1 and self.aliasUser
                ->forAll(base_Class <> null))
```

### B.1.26. WF RBACUser applied on a class cannot have any alias

If the stereotype «RBACUser» is applied on a class, it cannot have any *alias* association.

```
context rbacUML::RBACUser inv:
(self.base_Class <> null)
implies (self.aliasUser->size() = 0)
```

### B.1.27. WF A user partition and its corresponding user must have the same name

If an activity partition is stereotyped with «RBACUser», then it must have the same name as the class stereotyped with «RBACUser» and associated to the partition through the *alias* association.

```
context rbacUML::RBACUser inv:
(self.base_ActivityPartition <> null)
        implies (self.aliasUser
                ->forAll(base_Class.name = self.base_ActivityPartition.name))
```

### B.1.28. WF Roles activated on a user partition cannot break a DSoD constraint

The roles activated on a user partition cannot break any DSoD constraint. Therefore, if two roles participate in a DSoD constraint, they cannot be both activated on the same user partition.

```
context rbacUML::RBACUser inv:
self.rBACRole->forAll(role1, role2 | role1.dsod1->excludes(role2))
```

### B.1.29. WF Roles activated on a user partition must be assigned to the corresponding user

In an activity partition stereotyped with «RBACUser», all the associations to roles must be of roles that have been assigned to the partition's corresponding user.

```
context rbacUML::RBACUser inv:
(self.base_ActivityPartition <> null)
        implies (self.aliasUser.rBACRole
                ->union(self.aliasUser.rBACRole.base_Class->asSet().allParents().
                    oclAsType(Class).extension_RBACRole)->asSet()
                ->includesAll(self.rBACRole.base_Class.extension_RBACRole))
```

### B.1.30. WF A message referring to Restricted operations must be Restricted

All messages referring to operations stereotyped with «Restricted» must themselves be stereotyped with «Restricted».

```
context rbacUML::Restricted inv:
(self.base_Operation <> null) implies (self.allOwningPackages()->select(pkg | pkg.
    allOwningPackages()->isEmpty()).allOwnedElements()->select(elt | elt.oclIsTypeOf(
    Message)).oclAsType(Message)
        ->select(msg | msg.getAppliedStereotype('rbacUML::Restricted') = null).
            oclAsType(Message).signature.oclAsType(Operation)
        ->select(op | op = self)->size() = 0)
```

### B.1.31. WF A Restricted operation must be assigned at least one permission

An operation stereotyped with «Restricted» must have at least one association to a permission.

```
context rbacUML::Restricted inv:
(self.base_Operation <> null) implies (self.permission->size() > 0)
```

### B.1.32. WF A Restricted message must refer to a Restricted operation

Messages stereotyped with «Restricted» must refer to operations stereotyped with «Restricted».

```
context rbacUML::Restricted inv:
(self.base_Message <> null)
implies
(self.base_Message.signature.getAppliedStereotype('rbacUML::Restricted') <> null)
```

# B.2. Verification

## B.2.1. VER Forbidden verification

If an action is stereotyped with «Forbidden», then the roles activated by the user cannot give him/her enough permissions to perform *all* of the «Restricted» operations referenced by the action.

```
context rbacUML::Forbidden inv:
self.base_Action.inPartition.extension_RBACUser.rBACRole
        ->union(self.base_Action.inPartition.extension_RBACUser.aliasUser.rBACRole.
            base_Class.allParents().oclAsType(Class).extension_RBACRole)
        ->union(if (self.base_Action.extension_ActivateRoles = null) then Set{} else
            self.base_Action.extension_ActivateRoles.rBACRole endif)->asSet()
        ->symmetricDifference(if (self.base_Action.extension_DeactivateRoles = null)
            then Set{} else self.base_Action.extension_DeactivateRoles.rBACRole endif).
            permission
->includesAll(self.operation.extension_Restricted.permission->asSet()) = false
```

## B.2.2. VER Granted verification

If an action is stereotyped with «Granted», then the roles activated by the user must give him/her enough permissions to perform *all* of the «Restricted» operations referenced by the action.

```
context rbacUML::Granted inv:
self.base_Action.inPartition.extension_RBACUser.rBACRole
        ->union(self.base_Action.inPartition.extension_RBACUser.aliasUser.rBACRole.
            base_Class.allParents().oclAsType(Class).extension_RBACRole)
        ->union(if (self.base_Action.extension_ActivateRoles = null) then Set{} else
            self.base_Action.extension_ActivateRoles.rBACRole endif)->asSet()
        ->symmetricDifference(if (self.base_Action.extension_DeactivateRoles = null)
            then Set{} else self.base_Action.extension_DeactivateRoles.rBACRole endif).
            permission
->includesAll(self.operation.extension_Restricted.permission->asSet())
```

## B.3. Satisfiability

### B.3.1. SAT A Granted action should be executable by at least one user

Detects actions stereotyped with «Granted» that no user, with all their roles activated, can perform.

```
context rbacUML::Granted inv:
self.getNearestPackage().allOwnedElements()
        ->select(usr | usr.oclIsTypeOf(Class) and usr.getAppliedStereotype('rbacUML::
            RBACUser') <> null).oclAsType(Class)
        ->exists(usr | usr.oclAsType(Class).extension_RBACUser.rBACRole.permission->
            asSet()
                                        ->union(usr.oclAsType(Class).extension_RBACUser
                                            .rBACRole.base_Class.allParents().oclAsType
                                            (Class).extension_RBACRole.permission->
                                            asSet())
        ->includesAll(self.operation.extension_Restricted.permission->asSet()))
```

### B.3.2. SAT A Forbidden action should not be executable by every user

Detects actions stereotyped with «Forbidden» that every user could perform.

```
context rbacUML::Forbidden inv:
self.getNearestPackage().allOwnedElements()
        ->select(usr | usr.oclIsTypeOf(Class) and usr.getAppliedStereotype('rbacUML::
            RBACUser') <> null).oclAsType(Class)
        ->forAll(usr | usr.oclAsType(Class).extension_RBACUser.rBACRole.permission->
            asSet()
                                                ->union(usr.oclAsType(Class).
                                                    extension_RBACUser.rBACRole.
                                                    base_Class.allParents().oclAsType(
                                                    Class).extension_RBACRole.
                                                    permission->asSet())
        ->includesAll(self.operation.extension_Restricted.permission->asSet()))
```

### B.3.3. SAT Restricted operations should be executable by at least one user

Detects operations stereotyped with «Restricted» that no user can perform, because they require too many permissions.

```
context rbacUML::Restricted inv:
self.allOwningPackages()->select(pkg | pkg.allOwningPackages()->isEmpty()).
    allOwnedElements()
        ->select(usr | usr.oclIsTypeOf(Class) and usr.getAppliedStereotype('rbacUML::
            RBACUser') <> null).oclAsType(Class)
        ->exists(usr | usr.oclAsType(Class).extension_RBACUser.rBACRole.permission->
            asSet()
                        ->union(usr.oclAsType(Class).extension_RBACUser.rBACRole.
                            base_Class.allParents().oclAsType(Class).extension_RBACRole
                            .permission->asSet())
->includesAll(self.permission))
```

# B.4. Completeness

## B.4.1. COMP permission should be assigned to at least one role

Finds permissions that have not been assigned to any role.

```
context rbacUML::Permission inv:
self.allOwningPackages()->select(pkg | pkg.allOwningPackages()->isEmpty()).
    allOwnedElements()
        ->select(rl | rl.oclIsTypeOf(Class) and rl.getAppliedStereotype('rbacUML::
            RBACRole') <> null).oclAsType(Class)
        ->select(rl | rl.extension_RBACRole.permission->exists(per | per.base_Class.
            name = self.name))
->size() > 0
```

## B.4.2. COMP permission should be used by at least one Restricted operation

Finds permissions that are not used by any «`Restricted`» operation.

```
context rbacUML::Permission inv:
self.allOwningPackages()->select(pkg | pkg.allOwningPackages()->isEmpty()).
    allOwnedElements()
        ->select(op | op.oclIsTypeOf(Operation) and op.getAppliedStereotype('rbacUML::
            Restricted') <> null).oclAsType(Operation)
        ->select(op | op.extension_Restricted.permission->exists(base_Class.name = self
            .name))
->size() > 0
```

### B.4.3. COMP A role should be assigned at least one direct permission

Finds roles that have not been assigned any permissions.

```
context rbacUML::RBACRole inv:
self.permission->size() > 0
```

### B.4.4. COMP A role should be assigned to at least one user

Finds roles that have not been assigned to any user.

```
context rbacUML::RBACRole inv:
self.allOwningPackages()->select(pkg | pkg.allOwningPackages()->isEmpty()).
    allOwnedElements()
        ->select(usr | usr.oclIsTypeOf(Class) and usr.getAppliedStereotype('rbacUML::
            RBACUser') <> null).oclAsType(Class)
        ->select(usr | usr.extension_RBACUser.rBACRole->exists(rl | rl.base_Class.name
            = self.name))
->size() > 0
```

### B.4.5. COMP A user should be assigned at least one role

Finds users that have not been assigned any role.

```
context rbacUML::RBACUser inv:
(self.base_Class <> null) implies (self.rBACRole->size() > 0)
```

# B.5. Coverage

## B.5.1. COV Restricted operations should be used by at least one action

Finds «Restricted» operations that are not used in any action.

```
context rbacUML::Restricted inv:
self.base_Operation <> null implies
self.allOwningPackages()->select(pkg | pkg.allOwningPackages()->isEmpty()).
    allOwnedElements()
        ->select(act | act.oclIsKindOf(Action) and act.getAppliedStereotype('rbacUML::
            Granted') <> null).oclAsType(Action)
        ->select(act | act.extension_Granted.operation->exists(name = self.name))
->union(
self.allOwningPackages()->select(pkg | pkg.allOwningPackages()->isEmpty()).
    allOwnedElements()
        ->select(act | act.oclIsKindOf(Action) and act.getAppliedStereotype('rbacUML::
            Forbidden') <> null).oclAsType(Action)
        ->select(act | act.extension_Forbidden.operation->exists(name = self.name))
)->size() > 0
```

## B.5.2. COV A user should be represented on at least one user partition

Finds users that are not referenced in any activity partition.

```
context rbacUML::RBACUser inv:
self.base_Class <> null implies
self.allOwningPackages()->select(pkg | pkg.allOwningPackages()->isEmpty()).
    allOwnedElements()
        ->select(act | act.oclIsKindOf(ActivityPartition) and act.getAppliedStereotype(
            'rbacUML::RBACUser') <> null).oclAsType(ActivityPartition)
        ->select(act | (act.name = self.name) and (act.extension_RBACUser.aliasUser.
            base_Class = self))
->size() > 0
```

# B.6. Redundancy

## B.6.1. RED Redundant roles detected

Finds redundant roles. Roles are redundant if they have the same parents, the same children, the same permissions and the same SSoD and DSoD constraints.

```
context rbacUML::RBACRole inv:
self.allOwningPackages()->select(pkg | pkg.allOwningPackages()->isEmpty()).
    allOwnedElements()
        ->select(rl | rl.oclIsTypeOf(Class) and rl.getAppliedStereotype('rbacUML::
            RBACRole') <> null).oclAsType(Class).extension_RBACRole
        ->select(rl | rl.permission->includesAll(self.permission)
                        and rl.permission->size() = self.permission->size()
                        and rl.base_Class.name <> self.base_Class.name)
        ->select(rl | rl.allParents() = self.allParents())
        ->select(rl | rl.ssod1 = self.ssod1)
        ->select(rl | rl.dsod1 = self.dsod1)
->size() = 0
```

## B.6.2. RED Redundant users detected

Finds redundant users. Users are redundant if they have the same roles.

```
context rbacUML::RBACUser inv:
self.rBACRole->size() > 0 and self.base_Class <> null implies
self.allOwningPackages()->select(pkg | pkg.allOwningPackages()->isEmpty()).
    allOwnedElements()
        ->select(usr | usr.oclIsTypeOf(Class) and usr.getAppliedStereotype('rbacUML::
            RBACUser') <> null).oclAsType(Class).extension_RBACUser
        ->select(usr | usr.rBACRole->includesAll(self.rBACRole)
                        and usr.rBACRole->size() = self.rBACRole->size()
                        and usr.base_Class.name <> self.base_Class.name)
->size() = 0
```

# Appendix C.

# OCL Evaluation Performance Study Details

# C.1. Performance Evaluation Details

This section provides detailed tables for our performance analysis in Section 5.4. For each model size, 5 different models have been generated. The results were then aggregated by taking, for each model size, the average evaluation time. Here, we provide the data used for Figs 5.1 and 5.2.

Table C.1 details the evaluation time of verified models, Table C.2 details the evaluation time of malformed models, i.e. those that have failed the evaluation of well-formedness queries, and Table C.3 details the evaluation time of unverified models, i.e. models that have passed the well-formedness queries, but failed the verification queries. In those three tables, *size* is the size of the model (number of elements + number of associations), *Full* is the evaluation time of all the `rbacUML` queries in one pass, *WF* is the evaluation time of well-formedness queries only, *VER* is the evaluation time of verification queries only, *SAT* is the evaluation time of satisfiability constraints only, *COV* is the evaluation time of coverage queries only, *COMP* is the evaluation time of completeness constraints only, *RED* is the evaluation time of redundancy constraints only, *SUM* is the sum of the evaluation times of *WF*, *VER*,*SAT*, *COV*, *COMP* and *RED*, and finally, *LAZY* is the evaluation time of all the `rbacUML` queries using the lazy evaluation strategy.

**Table C.1.:** Evaluation times (in seconds) for verified models

| Size | Full | WF | VER | SAT | COV | COMP | RED | SUM | LAZY |
|---|---|---|---|---|---|---|---|---|---|
| 221 | 27.992 | 11.525 | 2.977 | 4.126 | 2.474 | 3.851 | 3.315 | 28.270 | 23.975 |
| 433 | 26.547 | 10.867 | 2.639 | 3.844 | 2.451 | 3.892 | 3.300 | 26.994 | 22.973 |
| 645 | 18.637 | 7.271 | 1.900 | 2.953 | 1.818 | 2.916 | 2.404 | 19.265 | 16.123 |
| 837 | 19.857 | 7.491 | 1.632 | 3.012 | 2.037 | 3.518 | 2.745 | 20.438 | 17.163 |
| 1033 | 21.290 | 7.800 | 1.196 | 3.026 | 2.320 | 4.295 | 3.187 | 21.826 | 18.572 |
| 2057 | 30.110 | 7.752 | 1.224 | 5.728 | 3.240 | 8.122 | 4.762 | 30.830 | 24.767 |
| 3074 | 44.378 | 7.622 | 1.231 | 10.194 | 4.728 | 14.511 | 7.357 | 45.644 | 34.873 |
| 4116 | 69.415 | 9.637 | 1.531 | 16.949 | 7.296 | 24.126 | 11.556 | 71.097 | 53.432 |
| 6168 | 134.108 | 12.627 | 1.922 | 35.267 | 13.900 | 50.458 | 22.644 | 136.819 | 100.211 |
| 8211 | 214.269 | 10.557 | 1.552 | 59.711 | 21.645 | 85.316 | 36.249 | 215.033 | 154.812 |

**Table C.2.:** Evaluation times (in seconds) for malformed models

| Size | Full | WF | VER | SAT | COV | COMP | RED | SUM | LAZY |
|---|---|---|---|---|---|---|---|---|---|
| 222 | 15.486 | 4.026 | 1.062 | 1.578 | 1.018 | 1.443 | 1.342 | 10.471 | 6.229 |
| 429 | 15.603 | 3.948 | 0.979 | 1.558 | 1.060 | 1.573 | 1.392 | 10.512 | 6.170 |
| 638 | 12.437 | 2.862 | 0.702 | 1.317 | 0.936 | 1.474 | 1.215 | 8.508 | 4.600 |
| 836 | 13.884 | 3.231 | 0.517 | 1.411 | 1.136 | 2.011 | 1.527 | 9.835 | 4.934 |
| 1039 | 12.261 | 2.511 | 0.456 | 1.613 | 1.068 | 2.127 | 1.472 | 9.249 | 5.249 |
| 2066 | 23.543 | 3.190 | 0.542 | 4.133 | 2.023 | 5.767 | 3.076 | 18.733 | 4.811 |
| 3090 | 38.925 | 3.419 | 0.588 | 8.213 | 3.376 | 11.441 | 5.447 | 32.486 | 5.069 |
| 4115 | 61.505 | 4.233 | 0.704 | 14.018 | 5.356 | 19.488 | 8.865 | 52.665 | 6.237 |
| 6156 | 122.027 | 4.878 | 0.750 | 30.415 | 10.761 | 42.340 | 18.270 | 107.416 | 6.344 |
| 8212 | 210.898 | 7.030 | 1.003 | 52.865 | 18.275 | 74.372 | 31.620 | 185.167 | 9.604 |

**Table C.3.:** Evaluation times (in seconds) for well-formed but unverified models

| Size | Full | WF | VER | SAT | COV | COMP | RED | SUM | LAZY |
|---|---|---|---|---|---|---|---|---|---|
| 221 | 27.754 | 11.532 | 2.978 | 4.096 | 2.428 | 3.830 | 3.284 | 28.151 | 27.877 |
| 433 | 27.422 | 11.271 | 2.621 | 3.905 | 2.527 | 4.044 | 3.405 | 27.775 | 27.552 |
| 645 | 30.157 | 12.162 | 3.149 | 4.623 | 2.686 | 4.419 | 3.612 | 30.653 | 30.370 |
| 837 | 29.178 | 11.526 | 2.417 | 4.301 | 2.788 | 4.791 | 3.787 | 29.612 | 29.366 |
| 1033 | 27.081 | 10.340 | 1.564 | 3.934 | 2.776 | 5.023 | 3.815 | 27.455 | 27.183 |
| 2057 | 38.823 | 11.505 | 1.763 | 7.838 | 3.842 | 8.859 | 5.552 | 39.360 | 39.190 |
| 3074 | 45.507 | 7.957 | 1.257 | 12.832 | 4.355 | 13.134 | 6.780 | 46.316 | 45.901 |
| 4116 | 72.536 | 10.761 | 1.666 | 21.856 | 6.827 | 21.881 | 10.843 | 73.836 | 73.151 |
| 6168 | 132.454 | 11.000 | 1.666 | 45.517 | 12.042 | 44.321 | 20.031 | 134.579 | 133.296 |
| 8211 | 217.618 | 11.745 | 1.699 | 78.667 | 19.303 | 75.391 | 32.892 | 219.699 | 218.322 |

## C.2. Generated Model

We reproduce in this section a small model generated by our model generator [4]. Below is the configuration we passed to the code generator to create the model. Many parameters can be set, and the model generator will aim to create a model with the specified number of elements and associations.

```
<models>
  <model name="lin0001">
    <well-formedness enforced="true" />
        <verification enforced="true" />
        <completeness enforced="true" />
        <coverage enforced="true" />
        <redundancy enforced="true" />
        <satisfiability enforced="true" />
        <users num="10">
          <roles min="5" max="5"/>
        </users>
        <roles num="10">
          <ssod min="0" max="0" />
          <dsod min="0" max="0" />
          <hierarchies min="0" max="0" />
          <permissions min="5" max="5" />
        </roles>
        <permissions num="10">
        </permissions>
        <partitions num="3" />
        <actions num="10" granted="5" forbidden="5">
          <operations min="5" max="5" />
          <restricted-operations min="5" max="5" />
        </actions>
        <operations num="10" restricted="10">
          <permissions min="5" max="5" />
        </operations>
        <classes num="3" />
        <activities num="1" />
  </model>
</models>
```

**Table C.4.:** List of inter-diagram associations for the randomly generated model

| Origin | End |
|---|---|
| restrictedOperation0 | permissions 1, 2, 3, 8 and 10 |
| restrictedOperation1 | permissions 2, 3, 5, 6 and 8 |
| restrictedOperation2 | permissions 1, 2, 6, 7 and 9 |
| restrictedOperation3 | permissions 3, 4, 5, 6 and 8 |
| restrictedOperation4 | permissions 1, 3, 5, 6 and 8 |
| restrictedOperation5 | permissions 1, 2, 4, 7 and 8 |
| restrictedOperation6 | permissions 4, 7, 8, 9 and 10 |
| restrictedOperation7 | permissions 3, 4, 6, 7 and 9 |
| restrictedOperation8 | permissions 1, 2, 4, 6 and 7 |
| restrictedOperation9 | permissions 2, 3, 6, 7 and 10 |
| User4 (partition) | no roles |
| User5 (partition) | roles 1, 2, 4, 6 and 7 |
| User9 (partition) | roles 4 and 9 |
| GrantedAction1 | «`Restricted`» operations 2, 4 and 6 |
| GrantedAction4 | «`Restricted`» operations 3 and 7 |
| ForbiddenAction4 | «`Restricted`» operations 7 and 9 |

The model is made of 10 users, 10 roles and 10 permissions. It actually is one of the models we used for the performance evaluation in Section 5.4. Elements are named according to their type and a counter. Fig. C.1 is the access control diagram, Fig. C.2 is the class diagram, and Fig. C.3 is the activity diagram.

The associations between the diagram are not visible. We have grouped them in Table C.4.

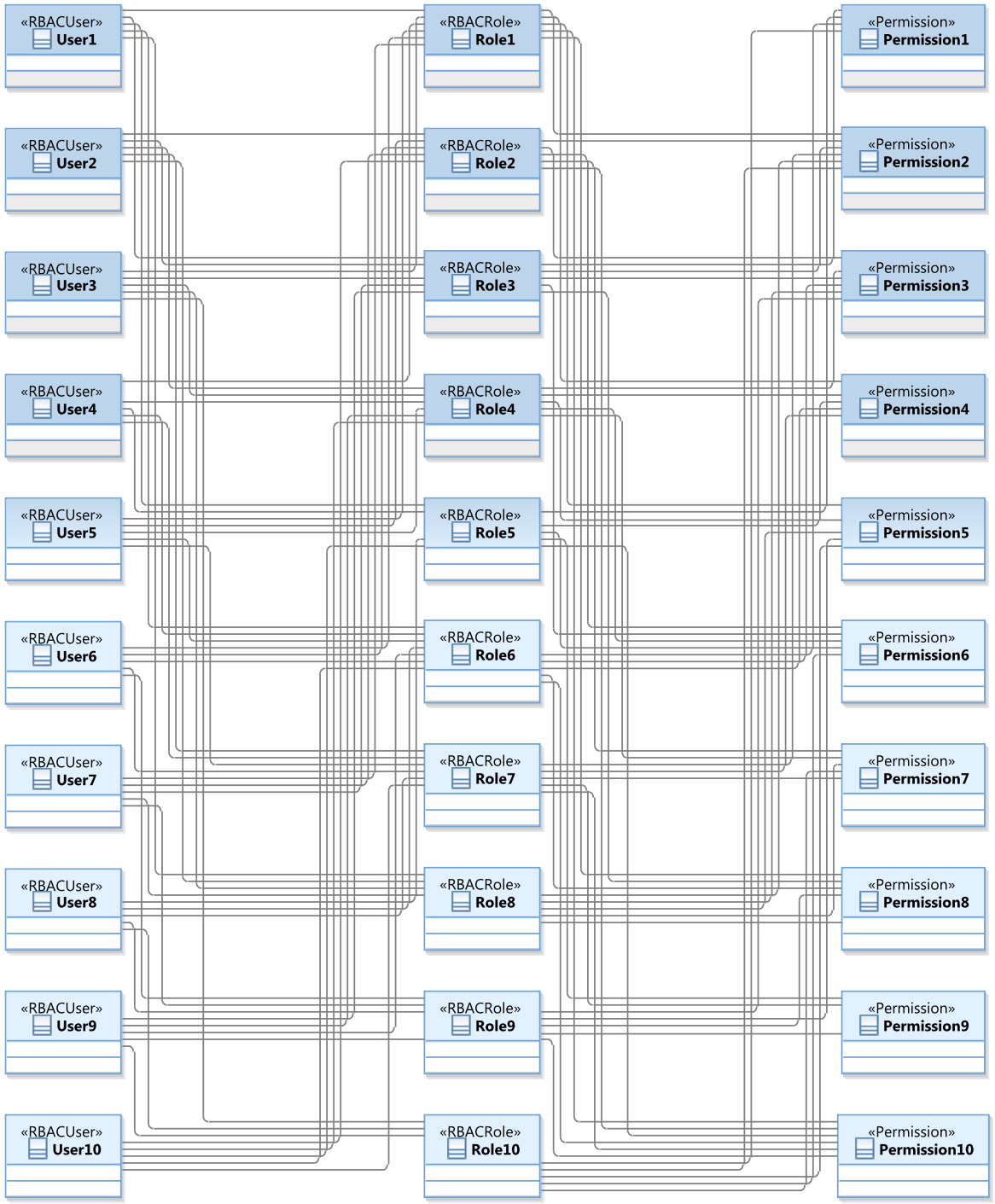


**Figure C.1.:** Access Control diagram for a small, randomly generated model

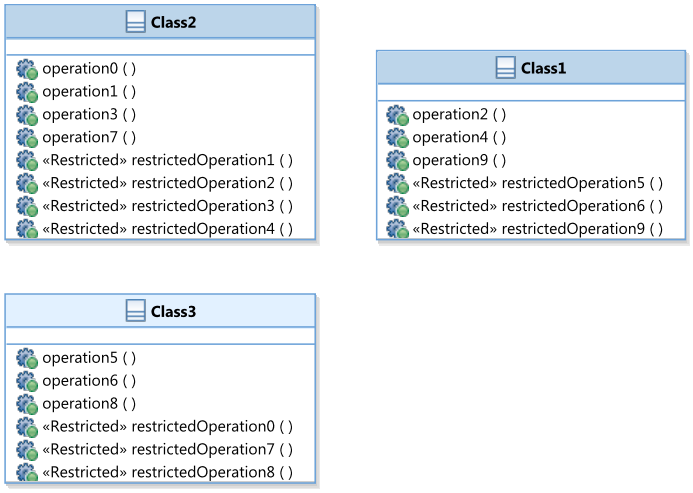


**Figure C.2.:** Class diagram for a small, randomly generated model

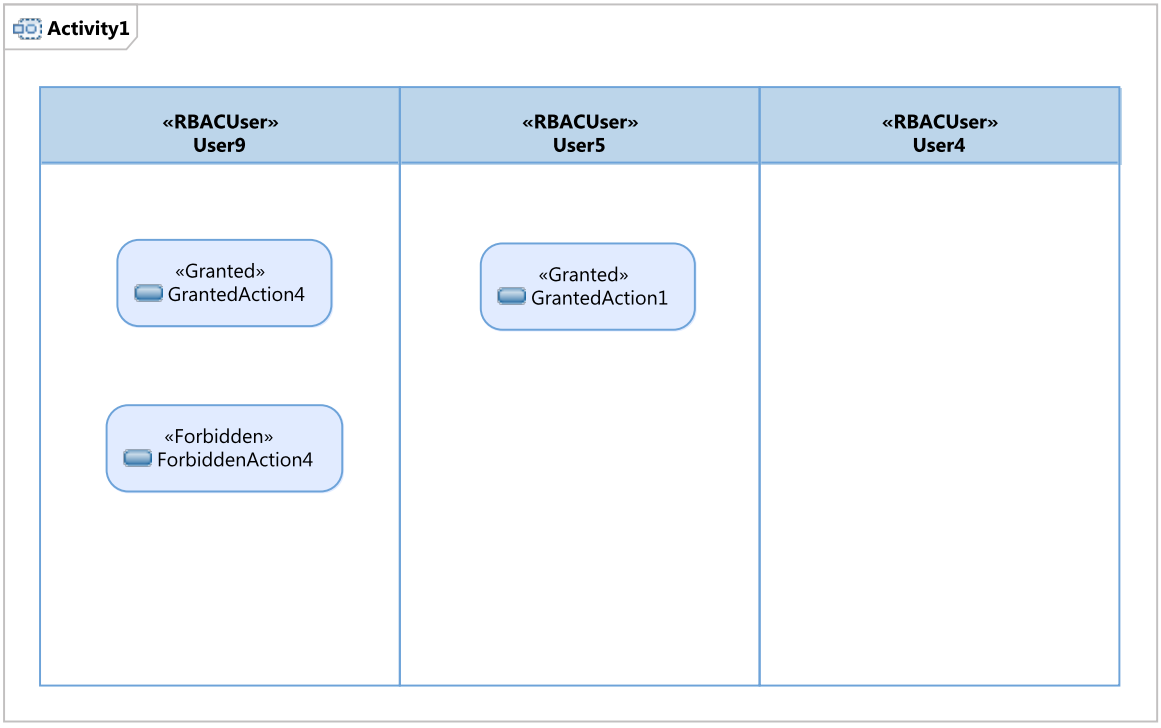


**Figure C.3.:** Activity diagram for a small, randomly generated model